CHAPTER 1

Radar—New Eyes for the Fleet

Beginnings of Radar

May Day—24 October 1944

Japanese scout planes found the ships of Admiral Frederick C. Sherman's Task Group 38.3 early in the morning of 24 October 1944, 90 miles east of Manila, protecting the U.S. Army invasion of Leyte Island. Soon after the sighting, the 51 Zero fighters of Number 3 Protective Squadron began turning up their engines. They were to fly top cover for the dive bombers and torpedo planes of the Imperial Japanese Naval Air Force's First Attack Group that had been assembled to annihilate the task group. The first of the 187 plane raid, the precursors of 'Operation Victory,' a massed air and sea offensive by which Imperial General Headquarters intended to reverse the fortunes of the Pacific war, broke ground from Mabalacat and Bamu Bamu Airfields near Manila at 0635 [108, pp.174–175].

At 0807 air search radar screens on the carrier *Essex* began to light up with a large number of targets 75 miles to the west, and ranging in altitude from 1,000 to 25,000 feet [108, p.xi]. The radar operators in each ship of the task force began sharing the radar tracking load, with each tracking only targets in an assigned wedge-shaped bearing sector. As the operators detected a new target, plotting officers assigned the target an identity (friendly, foe, or unknown) and a track number designating the reporting ship and the sequence in which it had been detected. Each ship announced the radar ranges, bearings, estimated altitudes, and identities of the targets in its sector by voice calls over a shared radio channel.

In the ship's combat information centers (CIC), sailors standing behind large plexiglass sheets marked with the spiderweb-like circles and spokes of a polar coordinate grid listened to raid reports on radio and telephone headsets. They grease penciled the positions of the reporting ships and their radar targets on the plexiglass sheets. Then, with mirror image writing, readable by those on the other side of the transparent 'vertical summary plots,' they wrote track numbers, speed, altitude, and raid size estimates next to the track symbols. Edge lighting on the plexiglass sheets made the grease-penciled markings glow so that officers and men in the darkened CIC spaces could see the evolving raid picture.

Aboard the flagship *Essex*, task group Fighter Director Officer (FDO) Lieutenant Junior Grade John B. Connally assessed the fighter and deck condition status boards of the Task Group 38.3 aircraft carriers: *Essex* (CV 9), *Lexington* (CV 16), *Langley* (CVL 27), and *Princeton* (CVL 23). He recalled all airborne fighters already on missions and scrambled available ready fighters from the four carriers. Then he assigned targets and groups of defending aircraft to fighter direction teams throughout the task group. At the moment, *Essex* had seven ready fighters about to be sent on a mission. The fighter directors scrubbed their mission and launched them, led by Commander David McCampbell, against the incoming aircraft [255, p.44].

Fighter direction team recorders plotted the positions of task force reporting ships on sheets of tracing paper laid over the polar coordinate grids marked on their round backlit plotting tables. Then with parallel rulers and pencils they plotted the bearings and distances of assigned attackers from the reporting ships. From elapsed time between target reports, they calculated target speeds and penciled them in near the tracks along with altitude and track numbers.

LTJG Connally checked his assignment board for a team to coach McCampbell's fighters to their targets. All teams were already at work, so Connally took over McCampbell's group himself. He eyed the plot of the oncoming attackers that McCampbell was to intercept, and laid out their heading/speed vector. With a maneuvering board he graphically calculated heading and speed for McCampbell to intercept them, as far from the task group as possible. Then he radioed speed, heading, and altitude directions to the climbing Hellcats. McCampbell's seven Grumman F6Fs were the first fighters of Admiral Sherman's task group to engage the Japanese air units, and five of his Hellcats attacked bombers and torpedo planes at medium altitude, while Connally sent McCampbell and his wingman, Lieutenant Roy W. Rushing, up to 25 thousand feet to engage the Zero fighters of the protective squadron.

When McCampbell sighted his assigned raid he radioed Connally that he and his wingman were outnumbered by more than 30 to one. This was the only time Connally ever sent out a 'May Day' distress call as a fighter direction officer. He asked all carriers to refuel, rearm, and scramble their fighters as soon as possible, and he directed all unassigned airborne fighters with enough remaining fuel and ammunition toward the incoming flights [255, pp.43–44].

Figure 1.1: The air plotting area of the new *Lexington's* (CV 16) combat information center during a strike in the Gilbert and Marshall Islands, November 1943. Fighter Director Officer, LCDR Allan F. Fleming, directs the plotting team from a high chair on the right. The tools of the fighter direction team: round, backlit plotting boards, radio and phone head and handsets, parallel rulers (behind LCDR Fleming's right arm), pencils, and dividers (far left) can be seen. *Photo by CDR Edward J. Steichen, courtesy of the Naval Historical Foundation.*

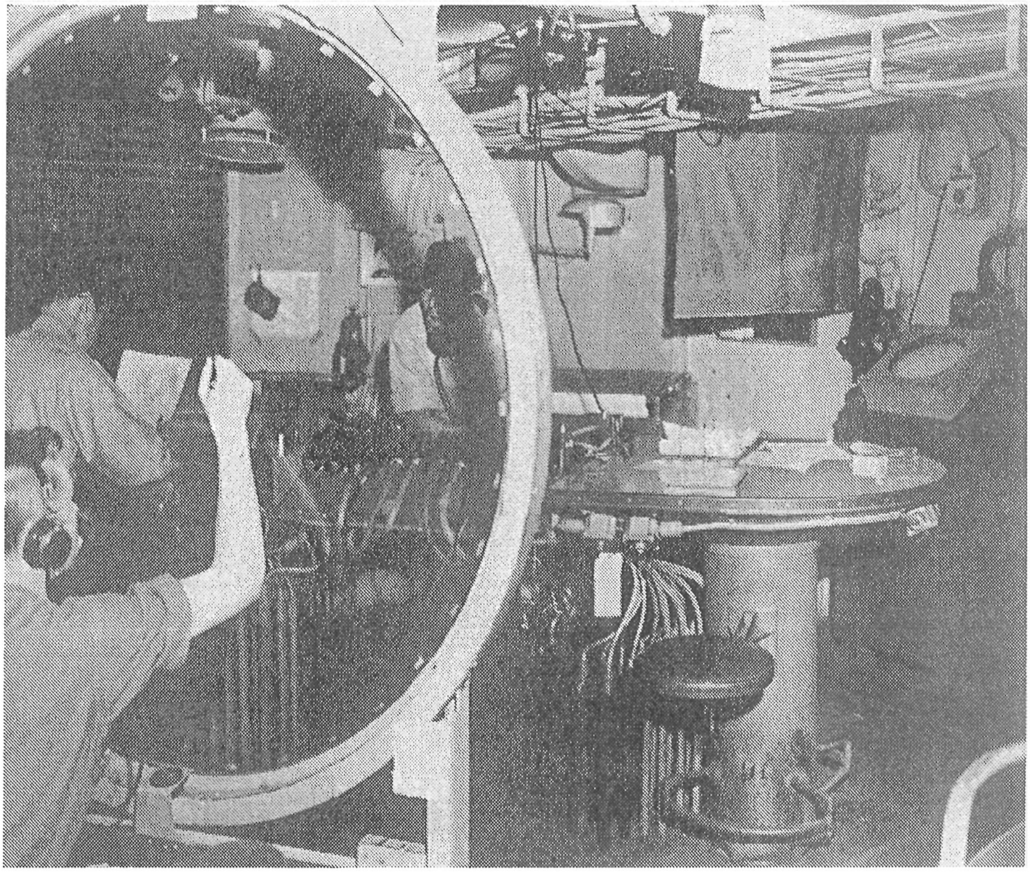

Figure 1.2: View of the USS *Guadalcanal* (CVE 60) combat information center, 3 June 1944, showing a sailor writing 'mirror image' characters on the plexiglass vertical summary plot, so those in front can read his writing. *Photo courtesy of the Naval Historical Foundation.*

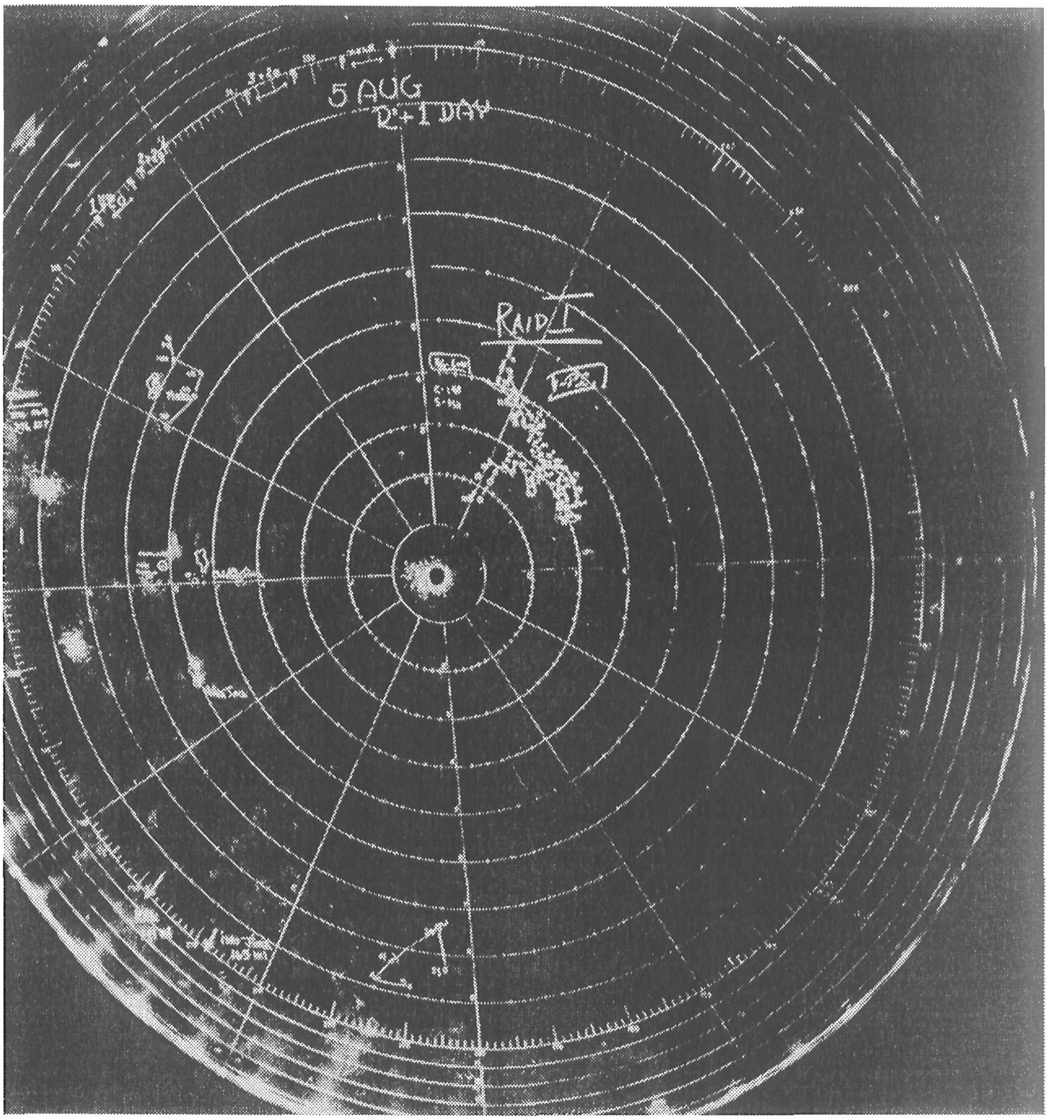

Figure 1.3: This is what the glowing grease-penciled markings on the vertical summary plot looked like in a darkened combat information center. Shown is USS *Hornet's* plot of Raid I as the carrier's aircraft were attacking targets in the Bonin Islands on 5 August 1944. *Photo courtesy of the Naval Historical Foundation.*

In 90 minutes of fighting McCampbell shot down at least nine Japanese planes while his wingman accounted for six, and LTJG A. C. Black, who had been called in to help, shot down five [108, p.175]. The pilots continued to thin the attacker's ranks, and only a few survivors made it past the fighters into the no-fly zone where the fighter directors turned the raiders over to the task group gunnery coordinators.

By electrical target designation transmitters or by sound-powered phones, the gunnery coordinators relayed target ranges, bearings, and elevation angles from the combat information centers to the guns and gun directors. Then the antiaircraft gunners of the encircling destroyer screen took over. Some of the attackers made it through the fire of the screening ships and what was left of them had to confront the AA guns of the heavies at the task group center. Most of the few bombers who made it to the shrapnel-filled skies over the center hurriedly dropped their bombs without effect and pulled up into the overcast to escape.

As useful as the task group's radar sets might be, they could not detect aircraft directly overhead. One raider of the No. 3 Bombardment Squadron stayed undetected in the clouds over the center of the task group, and, as the action shifted to another sector, and the sky over USS *Princeton* cleared of bursting AA projectiles, the bomber dove from its cover. Descending through a new hail of flak, it scored hits with two 550-pound bombs that went through *Princeton's* flight deck and exploded in the carrier's interior. Fires ignited by the bombs were soon fed by aviation gasoline. Six torpedo-armed TBF bombers on the hangar deck exploded next. *Princeton* continued burning and exploding until she had to be abandoned and then sunk by an American ship later in the day [210, p.155].

Even though the Japanese air fleet drew blood, this phase of Operation Victory was a failure. More than a third of the attacking Japanese aircraft were shot down with minimal aircraft losses to the defenders. The American fighters chased the survivors as far back as Manila, bringing down more on the way. The rest of Operation Victory went as poorly for the Japanese. In three days of fighting, the Japanese lost three battleships and four aircraft carriers compared to American losses of the fast carrier *Princeton*, two escort carriers, two destroyers, and a destroyer escort [210, p.155].

The air victories at Leyte Gulf were the result of finely practiced and well-directed teamwork. The team included the fighter pilots, the fleet gunners, the radar operators, and the fighter direction organization. The newest part of this team was the fighter direction organization. The second newest part was a device called radar that could locate ships and aircraft at distances far beyond the bounds of human vision, day or night and regardless of weather. Radar and its cousin, voice radio, had made the integrated fleet air defense team possible. Radio had been in the fleet since 1899, but the U.S. Navy had sent its first radars to sea barely in time to see action at the beginning of World War II. Furthermore, it was from experiments to improve naval radio communications that came the first glimpse of the possibility of using radio waves to locate objects at a distance.

Creation of Radar in the U.S. Navy

Start of the Naval Research Laboratory Radio Location Project

In September 1922 the engineers and scientists of the U.S. Naval Aircraft Radio Laboratory (NARL) in Washington, D.C., were housed in a building on the east bank of the Anacostia River, from which structure they had a clear shot across the river for testing radio transmissions. In mid September, two NARL engineers, Dr. A. Hoyt Taylor and Leo C. Young, were beaming high frequency radio transmissions to a receiver in a truck located across the river, when the customary 500 Hertz hum in the receiver's headset began to fluctuate with marked changes in loudness. They saw that a small wooden steamer, the *Dorchester*, was about to pass between the transmitting antenna and their truck, and they realized immediately that the steamer was causing interference with their transmission. They reasoned the changes in headphone sound were probably due to their transmitted wave 'bouncing' off the steamer and combining, sometimes in phase and sometimes out of phase, with the direct wave arriving at the receiver.

Though the two investigators were at first annoyed because they would have to wait until the steamer passed, they had second thoughts. These radio wave reflections, they conjectured, could be used to detect ships in fog or darkness. They could, perhaps, detect the presence of enemy ships or they could help prevent collisions of friendly ships. For example, freighters in a convoy could tell if a surfaced enemy submarine had come between them by the change in a transmitted tone.

After further experimentation, the two engineers wrote a proposal for a device that could detect the presence of ships by reflected radio waves. On 27 September 1922 their supervisor submitted the proposal to the Commanding Officer of the Anacostia Naval Air Station who sent it up the line to the Bureau of Engineering. The Bureau did not authorize work on the proposal because of other priorities such as an urgent program to expand fleet communications. Nevertheless, their experience planted an idea that would resurface from time to time over the next two decades, and would finally culminate in development of U.S. naval radar [91, p.171].

In July 1923 Naval Aircraft Radio Laboratory personnel and functions were absorbed into the newly established Naval Research Laboratory (NRL) which had been built on the site of an old Navy ammunition magazine at the southern point of the District of Columbia not far from the NARL facilities [3, pp.62–65]. As in the original NARL experience of 1922, when Taylor and Young unexpectedly detected the presence of a ship with reflected radio waves, in 1930, NRL engineers found quite by accident that airplanes could also be detected in the same manner. The investigators' real purpose had been to devise a radio landing aid for planes in darkness or fog. Their concept involved a receiver in the airplane that could detect a vertical radio beam and indicate to the pilot the direction to the transmitter. But they noted that the receiver not only showed the direction to the transmitter, but furthermore acted strangely whenever a stray airplane flew near the beam. More experimentation showed that the system could indicate the presence of planes out to a distance of 50 miles from the transmitter. NRL scientists worked out a design for a larger system whereby a grid of transmitters could detect and position-locate aircraft over a large area. But, because the equipment had to be disposed in stationary locations, the Navy again did not consider the idea useful in a naval environment.

The pieces of knowledge needed to develop an aircraft radio location system were falling into place. When, in 1934, Leo Young again proposed a scheme, this time wherein target range would be measured by timing how long it took for a short pulse of radio waves to travel out to a target and be reflected back, NRL was authorized to start a formal investigation of radio location. On 14 March 1934 Dr. Robert M. Page, assisted by L. R. Philpott, Robert C. Guthrie, and A. A. Varela, started the NRL radio location project. In December the pieces came together. For the first time they detected an airplane with radio pulses as it flew a pattern over the Potomac river. The radio detection system was made up of a 60 MHz transmitter feeding an antenna located on a laboratory building roof, plus a receiver with its antenna on another roof 150 feet away. A wire, running from the transmitter to the receiver, synchronized the receiver so that it could measure the round trip interval between transmitted pulse and receipt of a reflection back from the target [91, pp.172–173].

By April 1936 the NRL investigators had built a new set operating at 28.6 MHz, with which they detected and accurately range-tracked airplanes out to 25 miles. The twin transmitting and receiving antennas of the 28.6 MHz radar were too big for shipboard use, so they next devised a transmitter and receiver combination operating at 80 MHz to take advantage of the smaller antenna which the shorter wavelength allowed. Then, on 24 November, they tracked an air target in range out to 38 miles. More importantly, the NRL engineers invented a simple but effective antenna duplexer for the 80 MHz radio locator which allowed them to use one antenna for both transmitting and receiving [91, p.175].

In May 1936 the Laboratory started work on a 200 MHz radar incorporating the single-antenna duplexer with a Yagi 'fishbone' type antenna. The Yagi had the property of being able to transmit and receive in a narrow beam, and the antenna was small enough, thanks to the higher frequency, that it could be mounted on a rotating pedestal, allowing it to measure target bearing and elevation as well as range. NRL staff demonstrated the 200 MHz device to the Chief of Naval Operations (CNO) and the Assistant Secretary of the Navy on 17 February 1937.

The CNO authorized funds to test the device at sea, and NRL technicians installed the set in the destroyer *Leary* with the directional Yagi antenna clamped to a 5-inch gun barrel. During Atlantic Ocean testing in April 1937 it achieved detection ranges up to 20 miles. Commander-in-Chief, Atlantic Fleet was among those privy to the successful test results, and requested that the fleet be equipped with the new radio locating devices as soon as possible. Upon CNO approval, the Bureau of Engineering funded NRL in the amount of $25,000 to develop an operational shipboard radio locating set [91, p.180].

Tracking Projectiles in Flight—The Battleship New York Tests

A new radio location set based on the 200 MHz set design was ready to go aboard the battleship *New York* in December 1938. The Laboratory designated it Model XAF, and it incorporated every improvement devised by the Laboratory up to that time, one of the principal improvements being its 17×17-foot planar directional antenna. *New York* used the XAF in fleet exercises in February and March 1939 during which the new radio locator impressively demonstrated aircraft and surface ship detection, location of navigational aids, tracking gun projectiles in flight, and spotting the fall of shot. It tracked airplanes out to 100 nautical miles [91, p.180].

The fleet was sold on the XAF's early warning capabilities as well as its potential to help ward off at-sea collisions. They wanted more, and in May 1939 the office of the Chief of Naval Operations authorized 20 XAF radio detection sets to be installed in selected battleships, cruisers, aircraft carriers, and one seaplane tender. The Bureau of Engineering awarded a contract to the Radio Corporation of America to produce the 20 sets under NRL guidance. The first six sets off the production line were designated Model CXAM and the following 14, with improvements, were designated CXAM-1 [148].

The first production CXAM radar set was delivered to the battleship *California* where Commander Henry E. Bernstein, Naval Research Laboratory engineer Robert C. Guthrie, and Chief Radioman Joseph Leiper supervised installing and testing the set. (By 1942 both Bernstein and Leiper would be working in the Radar Design Branch of the Bureau of Ships [148].) Most of the 20 CXAM sets were in operation aboard fleet ships before December 1941 [91, p.183].

The CXAM's method of measuring target range was simple but effective. In the 1930s many laboratories had an electronic instrument called an oscilloscope using a cathode ray tube (CRT) which projected an electron beam onto a phosphor-coated glass viewing surface in the same manner that a television picture tube operates today. Voltages could be applied to horizontal and vertical beam deflection plates to cause the projected electron beam, and the resultant glowing spot where the beam collided with the phosphor, to be moved nearly instantaneously to any location on the viewing face. The oscilloscope was an obvious method to display XAF and CXAM radar returns.

When the CXAM transmitter sent out a pulse it also sent a trigger pulse to the receiver, causing the receiver to start a sweep circuit that sent the glowing spot moving at a constant speed from left to right across the cathode ray tube's screen. When the spot reached the far side of the tube it dropped downward a short distance and moved at the same rate back across the screen to the origin to make a rectangular sweep pattern. This back and forth pass was the 100-nautical-mile range sweep. Spot travel was timed so that it reached maximum display range at precisely twice the time required for the outgoing pulse to reach a range of 100 miles.

The radar sent the pulses out at a pulse repetition frequency (PRF) timed such that the pulse could travel out to a target at maximum display range and a reflection could return from the target just before the next pulse was transmitted. For example, it takes about 1.24 milliseconds for an electromagnetic pulse to travel 100 nautical miles and then return, so the PRF of the CXAM radar was set at 806 round trips per second. It can be appreciated that, with the glowing spot sweeping back and forth across the tube 806 times per second, the sweep pattern appeared to the eye as two glowing horizontal lines on the display tube.

Target returns coming back to the antenna were amplified in the receiver and then sent to the oscilloscope display tube where they were applied to the vertical deflection plate. The result was a glowing vertical spike, that the operators called a 'pip,' or sometimes a 'blip,' rising from the horizontal sweep line at a distance from the right or left sweep origin corresponding to target range. By comparing the spike location with calibrated range marks along the length of the horizontal sweep, the operator could read off target range.

The CXAM's rectangular, back-and-forth, range sweep arrangement made for accuracy in range measurement because it used twice the width of the tube, but it sometimes caused an operator perception problem because increasing-range direction for the first 50-mile segment was to the operator's right, whereas the increasing-range direction for the 50-to-100–mile segment was to the operator's left. Yet another problem with the 100-mile sweep limitation was the tendency of operators to interpret longer range 'second time around' target indications as targets in the first 100-mile sweep, regardless of design features to prevent this [148]. From these lessons the later SA, SC, and SK radars were designed with one continuous range sweep out to their maximum range. This single sweep presentation was called an 'A scope,' and became a standard radar display [118].

The Plan Position Indicator

While Dr. Page and his engineers were overseeing the 1939 Model XAF trials aboard *New York*, they observed that measuring target range and bearing was a cumbersome process for the radio location operators because they first had to read range off the scale on the A scope, and then look away from the A scope to get antenna bearing from a nearby antenna position 'syncro' receiver indicator. Syncro transmitter/receiver systems had been, and would remain for many years, a very accurate electromechanical means of transmitting quantitative information throughout a ship. A synchro transmitter/receiver pair has the outward look of two small electric motors connected to each other by wiring that can span a considerable distance. They are built so that the rotor in the synchro receiver is held locked in an electrical field causing the rotor to stay synchronized with the position of the rotor in the transmitter. Thus the position of the receiver's rotor will track the transmitter's rotor as it is turned, for example, by a radar antenna.

Back at the Laboratory, Dr. Page conceived a map type of radar display. He placed 'own-ship' at the center of a circular cathode ray tube so that the sweep traveled from the center of the scope to the periphery while the pulse went out and the echoes returned. Instead of a spike on the sweep to represent a target echo, the receiver momentarily brightened sweep intensity, leaving a glowing spot on the sweep line corresponding to target range. A synchro receiver and servomechanism arrangement rotated the scope's deflection yoke so that it always pointed the sweep line to the bearing at which the antenna was trained. The result: as the antenna rotated, the glowing sweep line also rotated like a spoke moving around the scope face, and it 'painted' small bright spots on the surface of the screen showing the locations of targets with respect to the ship. With a suitable phosphor coating on the tube, the spots persisted long enough for an operator to read and record target ranges and bearings. Dr. Page named his new display the plan position indicator, or 'PPI,' and he had laboratory models in operation by late 1939 [91, p.193].

The Baby Gets a Name

Until November 1940 the word 'radar' did not exist. The new radio location technology was addressed in a number of ways including: radio echo equipment, radio detection equipment, pulse radio equipment, and radio ranging equipment. The Navy had pursued development of the new equipment in absolute secrecy, and sometimes the devices were simply called radio direction finding equipment to hide them within an unclassified equipment category that already existed.

For Lieutenant Commanders F. R. Furth and S. M. Tucker, the Navy Department officers in charge of managing development of the new devices, the lack of some sort of standardized unclassified name was causing problems. Any name giving a clue that they could detect and measure the position of a distant target was classified secret, causing many letters and dispatches of a routine nature to be classified secret for no other reason than their reference to radio target location. Also, continued use of the many other identifying phrases was causing confusion and taking up precious space in naval messages.

Furth and Tucker devised the acronym 'radar,' which stood for radio detection and ranging, as a way to refer to the new technology in unclassified messages and letters. On 18 November 1940 the Chief of Naval Operations signed out a secret letter directing that henceforth the new devices would be called radar which, by itself, could be used in unclassified writings and conversations [91, p.170].

Mass Production

The CXAM radars needed 17×17-foot antennas that were too big for any but the largest ships, but by the end of 1941 the fleet had acquired a great liking for the CXAM and asked for something similar that could go aboard ships down to destroyer size. They also asked for longer detection ranges. The Bureau of Engineering had already tasked NRL to develop an improved radar, and by July 1941 the Lab had demonstrated the resultant higher power Model XAR radar aboard the destroyer *Semmes*. The XAR then served as progenitor of a series of production radars (Models SA, SC-1, and SK) that were able to provide detection ranges of 150 miles on average-sized aircraft. The Bureau of Engineering contracted with RCA and General Electric Co. to produce these radars in quantity [91, p.183].

By December 1941 Ensign Paul H. Backus aboard USS *Oklahoma* observed that radar sets were just coming into the fleet. During maneuvers, at least one of the heavies was usually carrying one of the rotating bedsprings mounted high on the superstructure, and radio reports coming from the ship with the bedspring antenna told of aircraft contacts at over 25 miles. This was incredible [9, p.50]!

The United States Navy was not the only organization to begin experiments on putting reflected radio waves to work. A number of investigators in other countries were also experimenting with radio location, with the result that some of these nations developed the capability almost simultaneously. In most cases military applications were obvious from the beginning, and in almost every case the projects proceeded independently and in great secrecy.

London—An Easy Target

Chain Home

The center of the city of London is less than 40 miles from the channel coast, and, as an aid to air navigation, the river Thames points like a glistening arrow to the heart of the city. London had suffered from German bombing in the 1914–1918 war, and since then aviation technology had made great strides. There were some in the leadership of Great Britain who felt there could be no stopping hostile bombing aircraft, not even with fighter airplanes. To them, the capital city of Great Britain appeared to be more vulnerable to destruction from the air than any other national capital.

New forms of anti–air defense seemed essential to the British Air Ministry, and in 1935 the Ministry's Director of Scientific Research established a Committee for the Scientific Survey of Air Defense, to be led by Professor Henry T. Tizard. The Air Ministry charged the committee of eminent scientists to evaluate all possible ideas and technologies, both old and new, that might be employed in the aerial defense of Great Britain. A death ray was one of the old ideas. For example, H. G. Wells in his 1897 *War of the Worlds* wrote of the invading Martians wielding a death ray. The board realized the concept was outlandish, but their task was to explore any possibility, and only after scientifically verifying lack of merit would they discount an idea.

As a consequence, in January 1935 Dr. Robert A. Watson-Watt, Superintendent of the National Physical Laboratory's Radio Research Department at Slough, England, issued a task to Arnold F. Wilkins, the laboratory's Scientific Officer. Wilkins' assignment was to calculate whether enough power could be concentrated in a radio beam to incapacitate a bomber pilot by making his blood boil (that is, a death ray). Wilkins' calculations confirmed that the concept was out of the question, even if only enough heating was required to raise a person's blood temperature to high-fever level. (If you have doubts that radio waves can warm you at all, consider your microwave oven.) Wilkins could have dropped the question there and gone back to work [29, pp.54,55].

But Wilkins remembered talking to British Post Office Engineers in 1931 and 1932 when they were experimenting with a communication system to link the Scottish islands with the mainland. They told him of the nuisance caused by radio waves reflected from passing airplanes that disrupted their experiments. Wilkins remarked to Watson-Watt that if the Air Ministry wished to use radio energy as a defense against bombers, they might consider using radio waves reflected from the skin of bombers for advance warning. In a few quick calculations he showed Watson-Watt that existing transmitter and receiver technology could create and detect reflected radio energy at tens of miles [72, pp.44–46].

On 12 February 1935 Dr. Watson-Watt submitted a proposal to the Air Ministry to build a device to detect aircraft at long distances by reflected radio waves. He backed up the proposal with Wilkins' calculations and he also included a description of a communications network that would use aircraft detection information to direct fighter pilots. The Air Defense Committee had its first real proposal, and three days later sent a request for development funds in the amount of £10,000 to Air Marshall Dowding, the Air Member for Research and Development [72, pp.60–61].

By March 1936 Watson-Watt had completed a prototype radar set and antennas, and had installed them at a test site, Bawdsey Manor, located on the English Suffolk coast at the mouth of the river Deben. Bawdsey would eventually become an operational site in a chain of wartime radar sites, called 'Chain Home,' that stretched along the English east coast from the southernmost station on the Isle of Wight, to the north station in the Orkney Islands. The antennas sat atop 250-foot towers at Bawdsey, with the transmitting antenna on a separate tower from the receiving antenna. Neither antenna rotated. The transmitting antenna radiated in all directions, with a shield placed on the landward side to prevent radiating inland. The sets operated in a range of frequencies from 10 to 25 MHz, and Watson-Watt designed them to be tunable to various frequencies to counter enemy jamming. At first the set designers had no way to determine target bearing. Instead, they conceived the radar chain as a curtain that would detect penetrating aircraft and measure their ranges.

Because their original concept did not include direction measurement, Watson-Watt deliberately called it a radio direction finding system to throw potential spies off the trail. By the time of installation at Bawdsey, Watson-Watt had solved the problem of bearing measurement by placing two horizontal dipole receiving antennas at right angles to each other. If a target was broadside to one of the dipoles, that dipole received most of the energy from the target return and the other dipole only a very small signal. On the other hand, if the target was on a 45-degree line between the two dipoles, they each received an equal return. If the target was anywhere in between, its relative bearing could be calculated from the relative strength of the two returns. By April 1937 Watson-Watt had four of the sites: Bawdsey, Canewdon, Dover, and Great Bromley in partial operation. Testing that summer brought just barely enough success to convince Air Marshall Dowding to continue building the remaining 16 sites [72, pp.116–125].

The Chain Home radar sites were only part of the solution. From the beginning, Watson-Watt's concept had included combining airplane detection information from radar installations and ground observer posts. All information was to go to a central plotting room to form a countrywide picture of the air situation. Also, if one radar site was down, data from adjoining sites would be available at the plotting center to fill the gap. From this big picture, the center could pick out the most threatening raids for earliest attention, ascertain the most probable raid targets, send warnings to the target areas, and provide local area information to subordinate control centers.

Watson-Watt designed a communications net based on buried telephone lines to tie Chain Home together, and most of the 'moving parts' in his system were human beings. The plotting center was underground at a most unlikely place, the ancient Monastery of Bentley Priory located in a northwest London suburb. The voice telephone lines from each Chain Home site ran to Bentley Priory, and the site radar operators, usually young Women's Auxiliary Air Force (WAAF) volunteers, phoned each aircraft position report to the 'filter room' at Bentley Priory. Filter room plotters assigned to each site plotted the radar data phoned from their assigned site. Most of the plotters were also WAAFs [72, pp.135–137].

We have all seen the classic photos and movies of these young women calmly moving their colored disks, red for enemy and black for RAF, across a large map table of England and the Channel. When they received a new track report they selected a new disk of appropriate color. On the disk they marked the time of the radar report to the half minute and put it on the table at the reported grid coordinates. If the report updated an existing track, they positioned a new marker, annotated with the new reporting time, showing the progress of the raid [28, p.3].

Filter room officers processed the radar data coming from the 20 sites. Their first step was comparing track data from one radar station with data from neighboring stations. Here they filtered out obvious errors and duplicate tracks. Then, from all available data, they estimated raid size, course, speed, and altitude; and they verified identity. They laid down direction arrows next to the markers and they penciled speed, altitude, and size estimates on the markers. A second tier of officers, located in a balcony above the map table, monitored the progress of the markers. They also had a view of a series of status boards, one board for each fighter squadron, which showed with colored lights the squadron's readiness or employment status. Given this information plus a knowledge of the location, particular characteristics, and capabilities of each radar station, these officers decided which site should take over track reporting for a particular raid [28, p.4].

Other filter room observers telephoned the filtered radar plot data to an operations room where plotters combined the radar data with aircraft sighting information phoned in by the Ground Observer Corps. The combined air situation plot was then ready to go out by phone to fighter group operations rooms spread about the English countryside. The group operations rooms, equipped with plotting tables similar to the Bentley Priory tables, concentrated on what was happening, or about to happen, within their geographic boundaries. The group operations officers then sent specific raid information to sector operations rooms where fighter direction officers ordered individual fighter scrambles, coordinated them with antiaircraft batteries, and vectored them to meet the incoming raids. In September 1938 during the Munich crisis, the first five Chain Home coastal radar sites went operational on a 24-hour basis, and when war came one year later there were 18 stations in operation, and the final two were almost ready [72, pp.138,183–184].

Wilkins and Watson-Watt realized at the outset of their experiments they needed a way to distinguish radio reflections bouncing off their own aircraft from returns reflected from enemy aircraft. Wilkins first developed a simple dipole antenna that could be mounted on friendly aircraft to enhance the reflected signal and make it look different from an unequipped airplane's return, but trials showed that the enhanced return was not sufficiently different from a normal reflection. Wilkins' solution was a powered radio device that transmitted a distinctively shaped pulse when triggered by a pulse from the Chain Home radar. Royal Air Force aircraft equipped with the experimental 'transponders' successfully demonstrated Wilkins' concept in the British air defense exercises of August 1935, and soon after, RAF officials approved the identification-friend-or-foe (IFF) sets for production and installation in all British aircraft [72, p.126].

Learning to Use Radar at Sea

The British were also quick to realize the payoff from fitting radar sets in aircraft to search out night-flying bombers and to spot surfaced submarines. Further, they saw the potential of radars aboard ship for early attack warning, fighter direction, and gunfire control. In August 1935, soon after Watson-Watt's first experiments, the Board of Admiralty directed the Experimental Department of the Royal Navy Signal School to start a shipboard radio-location development program [54, p.114]. By early 1940 the RN had underway a program of outfitting 23 major combatant ships with early warning radar, and under the stimulus of combat, made rapid strides in devising an afloat radar-assisted fighter direction organization [107, pp.56,99]. By late 1940 U.S. naval aviators were being detailed to Royal Navy aircraft carriers and RAF squadrons where they flew British aircraft and learned firsthand how the British were conducting air defense. In particular they learned the British system of radar-assisted fighter direction.

By early 1941 as the first of the exchange officers returned to the U.S. Fleet, they began setting up small informal radar plotting rooms in some aircraft carriers, similar to what they had seen in Royal Navy carriers. Then with experience gained in fleet exercises, some of the commanding officers of these ships proposed to the Chief of Naval Operations and the chiefs of the material bureaus that the major combatant ships carrying CXAM radars should be equipped with radar plotting facilities.

For example, in March 1941 the crew of *Yorktown*, the first U.S. aircraft carrier to be fitted with radar, was learning to use their newly installed CXAM, and, in a 29 March 1941 report to Commander-in-Chief, Pacific Fleet, *Yorktown's* CO noted the following about the new radar. On the positive side he reported that in practice exercises, combat air patrols "have been quickly and reliably directed to intercepts" by fighter direction officers using aircraft position reports from the CXAM. But, on the down side, the CO noted that the chief petty officers who operated the radar had to send their "unrelated and heterogeneous ranges and bearings" by sound-powered phone to Sky Control, Air Plot, Flag Plot, and the bridge for the men at these stations to use as best they could. He observed that the ship had no trained radar plotting team, no central radar plotting facility where tactical officers could see an overview of the entire exercise and, in particular, the fighter directors had hardly any working space. Commanding Officer, *Yorktown*, recommended, "Consequently there must be provided a RADAR plotting team, with adequate physical facilities for assimilating and segregating vital information [28, p.5]."

In July 1941 the Secretary of the Navy approved a joint recommendation from the CNO and the Chiefs of the Bureaus of Ships and Aeronautics, that major combatant ships should be equipped with a Radar Plot that would serve as the "brain of the organization which protects the fleet or ships from air attack." USS *Hornet* (CV 8), commissioned on 20 October 1941, was the first carrier to be equipped with such a radar plotting room during construction. *Hornet's* radar plot was in the island structure so that it could be close to the bridge, Flag Plot, chart house, Air Plot, and the radar set control room, all of which were furnished with voice tubes or sound-powered phone circuits for communication with Radar Plot. Special equippage in Radar Plot included remote gyrocompass indicators, radio receivers, remote radio transmitter control stations, a "plotting board of generous size and adapted to clear representation of the movements of several groups of aircraft," and a fighter patrol status board [28, p.6]. Older ships would have to make do as best they could until they underwent a major shipyard availability to get such a radar plotting room.

Hornet's new plotting space was designed to be operated in semidarkness, and was manned by:

- Two radiomen—who sent the coordinates of targets tracked by *Hornet* to other ships in the formation and received target coordinates from other ships.
- Two recorders—who, with pencils and parallel rulers, plotted own-ship's and remotely tracked targets on a back-lit plotting table.
- A plotting officer—who supervised the plotting. One of his main jobs was resolution of ambiguities and errors among tracks reported by more than one radar.
- A fighter direction officer—who was a principal user of the information on the radar plot [255, p.40].

The radar plotting room received target range and bearing measurements, height estimates and raid size estimates from the radar operators who, in own-ship, sent the data by sound-powered phone, voice tube or, in some cases, by messenger. From other ships, radio talkers sent the data by voice radio. The plotting room recorders marked the track of each target on the plotting boards, with own-ship or the flagship at the center of the coordinate system.

Under the new 'Tentative Doctrine for Fighter Direction from Aircraft Carriers,' published in August 1941, the flagship assigned air search sectors to specific ships in the formation. When an air search operator detected a new target in his sector, his ship had responsibility to continue to track that target and radio its coordinates to other participating ships. The radar operators kept track of all friendly targets, as well as unidentified and hostile targets, in order to help keep the friendlies out of harm's way and to keep the fighter directors informed where their assigned fighters were [255, p.40]. It was axiomatic that if the tactical commanders knew where all their friendly aircraft were, any unidentified airplane could be classified hostile.

The Most Valuable Cargo

Naval ships did not have the same luxury of real estate as did the Chain Home system to accommodate large radar antennas. This space restriction therefore imposed a limitation on shipboard radar performance for a given transmitter power, the relationship between antenna size, power, and operating frequency being: the shorter the wavelength, the smaller the antenna needed to transmit a given amount of power. The most severe problem with which airborne and shipboard radar designers grappled was therefore that of generating large amounts of radio energy at higher and higher frequencies. Aircraft especially demanded very small antennas calling for transmitters operating in the upper part of the ultra high frequency (UHF) band (300 to 3,000 MHz) or higher. But existing vacuum tubes could generate little useful power at those frequencies, and 400 to 600 MHz was the end of the line for useful vacuum tube performance during WW II [118].

As early as the summer of 1939 the British Government had tasked Professor Mark Oliphant, head of the Department of Physics of the University of Birmingham, to develop a 'valve' (electronic vacuum tube) capable of generating radio energy at very short wavelengths to alleviate the shipboard and aircraft antenna size limitation problem. What they were looking for was wavelengths measured in centimeters, with enough radiated power to locate small objects such as submarine conning towers and airplanes at long range. Oliphant divided his laboratory staff into small teams to explore concepts, Professor John T. Randall and graduate student Henry A. Boot forming one such two-man team. They tried a few ideas to no avail and then continued to study the literature of physics and electronics for clues [72, p.249].

Randall and Boot zeroed in on two possible microwave generation technologies, neither of which by itself could generate the large amounts of centimeter wave power for which they were searching. The first was the magnetron tube invented in 1916 by General Electric engineer Albert W. Hull in a search for alternatives to the vacuum tube in certain applications. Instead of using an electrically charged grid to control electron flow, Hull had devised a scheme whereby a variable magnetic field took the place of the grid. Hull also reported in the scientific literature that at certain plate voltages and magnetic field combinations, his magnetrons broke into unwanted oscillations—at microwave frequencies [118].

In early 1939 the brothers R. H. and S. F. Varian published a report of their progress on a new radio frequency oscillator vacuum tube called a klystron. Their tube used the propensity of a cavity hollowed out in a block of metal to electrically resonate at microwave frequencies when an electric pulse was introduced at the cavity's opening. In their scheme they passed a beam of electrons over the cavity opening which sustained the cavity's resonation, and they found they could extract small amounts (on the order of 10 watts) of centimeter wave power from the tube [23, p.330].

In a brilliant amalgamation of these two completely separate lines of research, Randall and Boot decided to combine the magnetron with the resonant cavity klystron, and they chose to use eight cavities to increase coupling with the spiraling electrons; hopefully to increase direct-current-to-microwave conversion efficiency. On 21 February 1940 Randall and Boot assembled their fist-sized machined copper block, put it between the poles of a magnet, and connected it to their direct-current-pulsed high-voltage power supply. After they blew out two sets of automobile headlights with the resultant microwave energy, a set of neon floodlights finally carried the load, which they measured at 100 kW peak pulse power, 400 watts average power, at a frequency of 3,053.8 MHz (just under 10 cm wavelength) at an efficiency of over 30 percent [72, p.250][220, p.199]. For comparison, the best that conventional vacuum tube circuits could do at that frequency was 10 watts.

In his position as head of the Committee for the Scientific Survey of Air Defense, Professor Henry T. Tizard had an overview of the numerous wartime scientific breakthroughs being made by British academia and industry. Most of these, such as the jet engine and radar, were under the tightest of security wraps, and his concern was that the United States, which was becoming 'the arsenal of democracy,' did not have the advantage of this new knowledge. On the other side of the coin, he reasoned that the Americans might have new technology that could be useful to Great Britain in its darkest hours.

In early 1940 Tizard proposed to Prime Minister Churchill that a joint scientific and technical exchange program should be established with the Americans, and by that summer Churchill acknowledged the British situation was serious enough to warrant sharing their most precious military secrets with the United States. The Prime Minister instructed Tizard to assemble the mission and to select the technologies to be revealed. Churchill also secured President Roosevelt's cooperation to ensure there would be open trade. Churchill's instructions to Tizard were to tell everything.

The Tizard Mission, made up of engineers and scientists who had developed the technologies, plus military officers who were using the new devices, left for the United States in August 1940. One of their stops was to be the Naval Research Laboratory in Washington, D.C., where they were to reveal the secrets of radar [29, pp.31–36].

Warrant Radio Electrician Irvin L. McNally had been in the Warrant Officer's Engineering School at the Naval Research Laboratory since June 1940. He was in the first group of U.S. Navy Warrant Radio Electricians to receive formal radar instruction, and he had studied the technology at NRL, at the Massachusetts Institute of Technology, and at various industrial laboratories. It was now September and McNally was looking forward to a year more of studies combined with instructing classes in radio physics and mathematics.

Dr. Robert M. Page, head of the NRL Radio location project, as well as being one of McNally's teachers, was aware of McNally's interest in radar, and invited McNally to sit in on a meeting with a visiting British delegation to whom Page had been instructed to tell everything about the Naval Research Laboratory's radio location project. There were some mutual surprises that day. Both groups found that the other had operational radar devices in their fleets. The British were delighted to learn about Dr. Page's antenna duplexer that allowed using one antenna for both transmitting and receiving.

Page was somewhat dismayed to learn of the British plan position indicator display, which the British had in production. That night A. A. Varela, one of Page's engineers, took McNally to an NRL back room and showed him NRL's PPI which would soon go into production [148]. Even though Page had filed his PPI patents at about the same time that the British had filed, the British had clearly stolen a march on the NRL plan position indicator. A few days later the Americans were astounded by the cavity magnetron presented by Dr. E. G. 'Taffy' Bowen, in charge of British airborne radar set development [121, p.75]. NRL had been striving, with indifferent results, to develop such a device that could produce usable power output at microwave frequencies.

The British magnetron created a shock wave among the U.S. technical institutions that had been searching for such a device. High-power microwave generation had been of such priority in the United States that a Microwave Committee had been formed under the United States National Defense Research Committee. On 28 September the Microwave Committee met with Taffy Bowen and laid the groundwork for a joint microwave radar development program. The historian of the American Office of Scientific Research and Development later described the British cavity magnetron as "the most valuable cargo ever brought to these shores [29, pp.27,40]." Warrant Radio Electrician Irvin L. McNally had been among the first Americans to see that cargo.

Irvin McNally had graduated from the University of Minnesota in June 1931 with a bachelor's degree in electrical engineering, but it was the bottom of the Great Depression, and not one new electrical engineer in his graduating class got a job offer. McNally had been a work-study student with Bell Telephone Company, however even that connection yielded no job. McNally was also an Army Reserve Officer's Training Corps student, which resulted in a commission as second lieutenant in the Signal Corps Reserve followed by six weeks of active duty.

While on active duty, McNally inquired of Captain H. C. Roberts, his senior officer, about the possibilities of civilian employment in Army communications. Roberts was not optimistic, but he had formerly cooperated with the Navy in communications developments, and was impressed with the strides the Navy was making in communications technology. He advised McNally to enlist in the Navy as a communications specialist for four years, get some good practical experience and weather the hard economic times. McNally took the advice, and upon his return to Minnesota was able to secure one of the few 1931 recruit quotas allocated to the Ninth Naval District. In February 1932, following 'boot camp' at Great Lakes, Illinois, McNally left for the Navy Radio School in San Diego. There he entered into a pattern he was to experience many times in his Navy career. Because he was a graduate electrical engineer and also a qualified radio operator, he was assigned to teach.

McNally explained to the school's commanding officer his desire to get practical experience in Navy communications at sea. He was convincing, and he received orders to the fleet commander's communication staff aboard the battleship *Pennsylvania*. The ship had one of the most extensive radio communications installations in the fleet, and McNally gained a wealth of experience in all phases of radio. By 1936 he had risen to Radioman First Class aboard *Pennsylvania*. His four year enlistment was drawing to a close but he was thriving on his work, and he could see a possible route upward in the Navy as a warrant officer. However, in addition to passing a tough technical examination, one of the prerequisites for warrant officer appointment in the area of radio was completion of the Radio Material School given at the Naval Research Laboratory. McNally's seniors backed him, and in 1936 *Pennsylvania* issued him temporary additional duty orders to the school. Again, after the school administrators reviewed his background, they made McNally an instructor as well as a student.

For McNally, the school had a number of fringe benefits, chief of which was his opportunity to meet and learn from Dr. Page and his team of scientists who were beginning their work on radio location. After both teaching and studying at radio material school he took a course in sonar followed by a course on the Adcock radio direction finder. Then in late 1936 McNally reported back aboard *Pennsylvania* where he took the next Radio Electrician Warrant exam in 1937. McNally was very glad for his NRL experience and his degree in electrical engineering. The week-long exam had college level questions in electronics as well as questions on diesel engine theory, current events, geography, military history, and even close order drill. He passed and received an appointment as Warrant Radio Electrician in December 1937.

In a way, McNally thought he had found the best of all possible worlds. The shipboard quarters assigned to warrant officers were equal to those assigned to commissioned officers, but the social and administrative demands were considerably less than those placed on commissioned officers. McNally was happy to be free of the many social obligations of the wardroom officers. The Navy discouraged warrant officer fraternization both with commissioned officers and with enlisted men, causing the warrant officers to be a close-knit and supportive group, who were in their unusual positions because of outstanding expertise in some particular field.

McNally was detached from *Pennsylvania* in January 1938 and ordered to the staff of the Sixteenth Naval District located at Cavite in the Philippines. From Cavite he was dispatched to the American Consulates at Canton, Swatow, Amoy, and Foochow, China, to install radio listening stations for intercepting Japanese military radio traffic. During this time he met his future wife Gracie who was enjoying an Asiatic steamer tour. Upon his return to the Philippines, McNally was detailed to Corregidor to help install a radio station, and, while doing so, he made a number of friends, many of whom were tragically not destined to survive the coming conflict.

By June 1940 McNally was a repeat offender at the Naval Research Laboratory where he had been ordered back to attend the Warrant Officer's Engineering School, the main thrust of which was to learn the new technology of radar—in depth. The first phase of the course was instruction on the Laboratory's Model XAF 200 MHz air search radar, taught by its inventors: Dr. Page, Dr. Taylor, and Messrs. Guthrie, Young, Distad, and Varela. McNally then visited radar laboratories at the contractors who were building the first U.S. Navy radar production radars, including Westinghouse, Bell Laboratories, RCA, and General Electric. This was followed by radar lectures at MIT and then, after the Tizard Mission, came briefings by the British Technical Staff.

When the time came in June 1941 for NRL to present the first formal course in radar offered to U.S. Naval Officers, McNally was again one of the instructors rather than the instructed. He was assigned to teach radio physics and mathematics, and during this time he also wrote several chapters for CDR Nelson M. Cooke's book, *Mathematics for Electricians and Radiomen*. McNally and four other warrant radio electricians taught the four-month course to 59 officer students, four of whom then went on to teach the Navy radar course at MIT. However, most, including Edward C. Svendsen, a young ensign recently graduated from the U.S. Naval Academy, were slated to report to ships as radar officers. We will hear more of Svendsen.

Commander Daniel C. Beard had been Officer-in-Charge of the Radio Material School at NRL when McNally attended to get his warrant officer qualification. By mid 1941, Beard was fleet electronics officer on the staff of Commander-in-Chief, Pacific Fleet, at Pearl Harbor, and one of his tasks was to establish a Pacific Fleet Radar Maintenance School to help overcome a critical shortage of trained radar technicians. He remembered McNally and asked for him to be sent out to establish the school and to be its Officer-in-Charge. McNally received orders to the CINCPAC staff and was detached from NRL to leave for Pearl Harbor on 1 November 1941.

McNally and Gracie left Washington, D.C., and set out across country in their Pontiac. From his daily ledger he calculated the trip cost them a total of $61.07. He left Gracie with her family in California, from where she was to travel to Hawaii after he had found suitable quarters. He then took passage to Pearl Harbor on the Army Transport *Republic* [147].

Radar at War in the Pacific

McNally's Day of Infamy

McNally reported to CINCPAC headquarters at the Pearl Harbor Naval Base on 1 December 1941, and then set out to find temporary living quarters. He checked in at the navy base bachelor officers quarters, but was advised in no uncertain terms that warrant officers were not authorized to stay at the BOQ. The warrant rank was basically a seagoing rank and little thought was given to their accommodation ashore unless they were assigned to a shore activity such as a radio station where the activity would make quarters available. McNally reviewed his possibilities for a place to stay. He could get a hotel room in Honolulu, he could try the local ships that might have warrant accommodations or he could pitch a tent

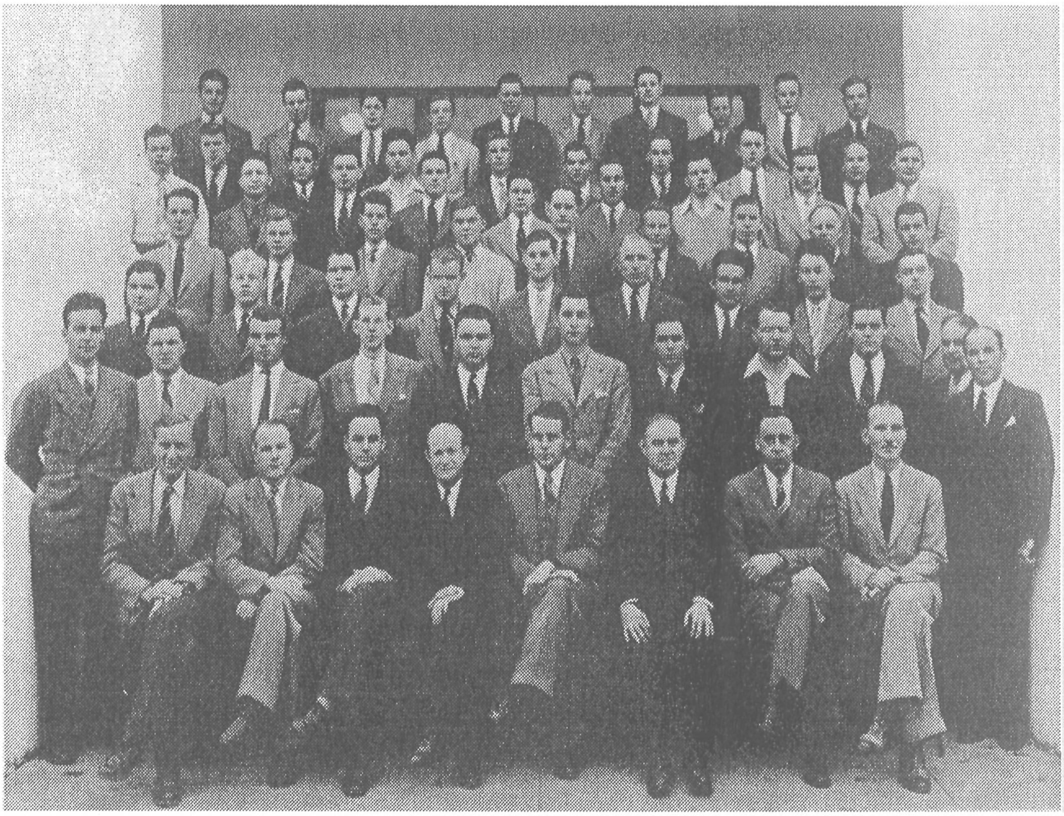

Figure 1.4: Graduates, instructors, and staff of the first U.S. Navy officers' radar school in October 1941. The course, given at the Naval Research Laboratory, lasted four months and was instructed by five Warrant Radio Electricians, all of whom are seated in the front row: John R. True, far left; Floyd C. Atnip, second from left; Irvin L. McNally, third from left; Otto C. Miller, second from far right; and Willard Triska, far right. Most of the graduates went to shipboard radar officer billets. Ensign Edward C. Svendson, top row, far left, became the battleship *Mississippi's* first radar officer and later her first combat information center officer. *U.S. Navy photo, courtesy of Irvin L. McNally.*

on the lawn and bring the matter to a head. Before resorting to such civil disobedience, however, he decided to review the roster of ships in port, wherein he found that his old ship, *Pennsylvania*, was tied up at 1010 dock, and he knew he had friends aboard. He made his way over to the ship where one of his old shipmates, Warrant Electrician Brown, was glad to share his room.

During the next few days Commander Beard and McNally drove around the base looking for a suitable place to build the radar school. They found a good site at the old coaling dock, and McNally began to draw up plans for classrooms and locations to install heavy radar equipment. On Saturday, 6 December, McNally spent the day visiting an old friend, Dudley Smith, in Honolulu, where he was invited to stay overnight. But McNally had to decline the invitation because he had invited ice skating friends to come aboard *Pennsylvania* to watch the Sonja Heine movie that evening after dinner. He did promise to return to the Smiths Sunday afternoon, and to lighten his load for the round trip he left his movie camera and other photo equipment at their home. He had also found an apartment in Honolulu and had sent a telegram to Gracie to book passage to Hawaii [147].

Because of the landlocked nature of ship's berths in Pearl Harbor, it was standard practice that the ships did not use their radars in harbor. Instead, six Army mobile search radar sites ringed the island of Oahu, using a Westinghouse-built Signal Corps radar. At 0702 the following Sunday morning, the two Army Signal Corps operators of the SCR-270 mobile radar stationed at Opana on the northern tip of Oahu, detected one of the largest spikes they had ever seen on their A scope. It was at a range of 136 miles and due north. Privates Joseph L. Lockard and George E. Elliott checked the set to make sure it was not malfunctioning. The track was real and the two operators began to plot it. From the deduced speed, the track had to be a large number of aircraft heading straight south toward the island.

At about 0720 Lockard phoned the Oahu Central Information Center. The track was adjudged by the Information Center watch officer to be either a returning naval patrol, a flight of bombers from Hickam Field, or a flight of B-17 bombers from the mainland. He told Lockard there was no cause for alarm. The radar site was scheduled to shut down at 0700, but the two privates continued tracking the incoming target until 0739. The huge blip was then in to 20 miles, and sea clutter was starting to obscure the signal. They secured the operation a few minutes later when the truck arrived to take them to breakfast [1, p.38].

McNally awoke at 0730 on Sunday morning aboard *Pennsylvania* which was now in Drydock No. 1, sharing it with the destroyers *Cassin* and *Downes*. Before returning to the Smith's home, CDR Beard had asked him to go over to USS *California* and talk to CDR Henry Bernstein about work Bernstein was doing with a prototype IFF set for *California's* CXAM air search radar. It was just about 0800 and McNally was ready to leave the ship. He was going to wear civilian clothes, and District uniform regulations required that officers wear a hat ashore. (McNally notes we may have had our pants down but we were wearing our hats.)

McNally was just trying on one of Brown's civilian hats when he heard a tremendous explosion. He stuck his head out of the compartment porthole to see what had happened. There he saw an airplane with red circle markings, carrying the longest torpedo he had ever seen, just skimming the roof of the dockside shop. His first thought was, "The Japanese are here!" His second thought was one of regret, "Good Lord, my movie camera is ashore."

McNally ran to Main Radio where he had served for many years, and told the men on watch that the Japanese were attacking the base. Then he went back to the warrant officer's mess to help set up a battle dressing station. On his way he saw the harbor was a shambles of burning and exploding ships, and he watched with disbelief as the battleship *Oklahoma* capsized, bringing her screws high in the air. He thought of the poor souls being trapped in her hull. When he got to the dressing station, the doctor on duty asked McNally to go below and get battle helmets, and in compliance he slid down two ladders to the third deck, just below the top of the battleship's 5-inch-thick 'armored box.'

Just as he reached the deck there was a shuddering explosion directly overhead. The lights went out, and the hatchway through which he had just come was blocked by burning debris. He began to feel butterflies in his stomach but recalled there was more than one way to return topside. He got the helmets and made his way over to the port side where he climbed up and made his way back to the battle dressing station where he found a scene of destruction, with many dead and wounded. The young doctor who had asked him to get the helmets was among those killed.

A bomb had hit the base of one of the casement guns just outside the warrant officer's mess and had blown up the boat deck, the galley, and one side of the junior officer's bunk room. The dead and wounded were mixed up in the burning debris, and were burned black as charcoal. Some were horribly mangled. One body had been blown up through the boat deck and was draped over one of the boat skids, while another had a 2-inch furrow plowed through his forehead. Had McNally not gone for the helmets, he would have been one of them.

The battle dressing station was destroyed, so McNally and the other survivors got mattresses from the junior officer's bunkroom and used them as litters to carry the wounded forward to the sick bay. The most pitiful were the badly burned who could hardly be recognized. McNally would never forget the sight of the corpsmen passing among the wounded with morphine syringes to ease their suffering.

McNally went topside and saw that *Cassin* and *Downes* had been hit by bombs and were burning fiercely just under *Pennsylvania's* bow. Shipyard workers had to flood the dry dock in an attempt to put out the fires. By this time the ships' guns were putting up a curtain of antiaircraft fire, and he saw one direct hit, but in most cases the shells exploded far below the airplanes. In later years McNally would muse what a difference the radar variable time fuse would have made that day.

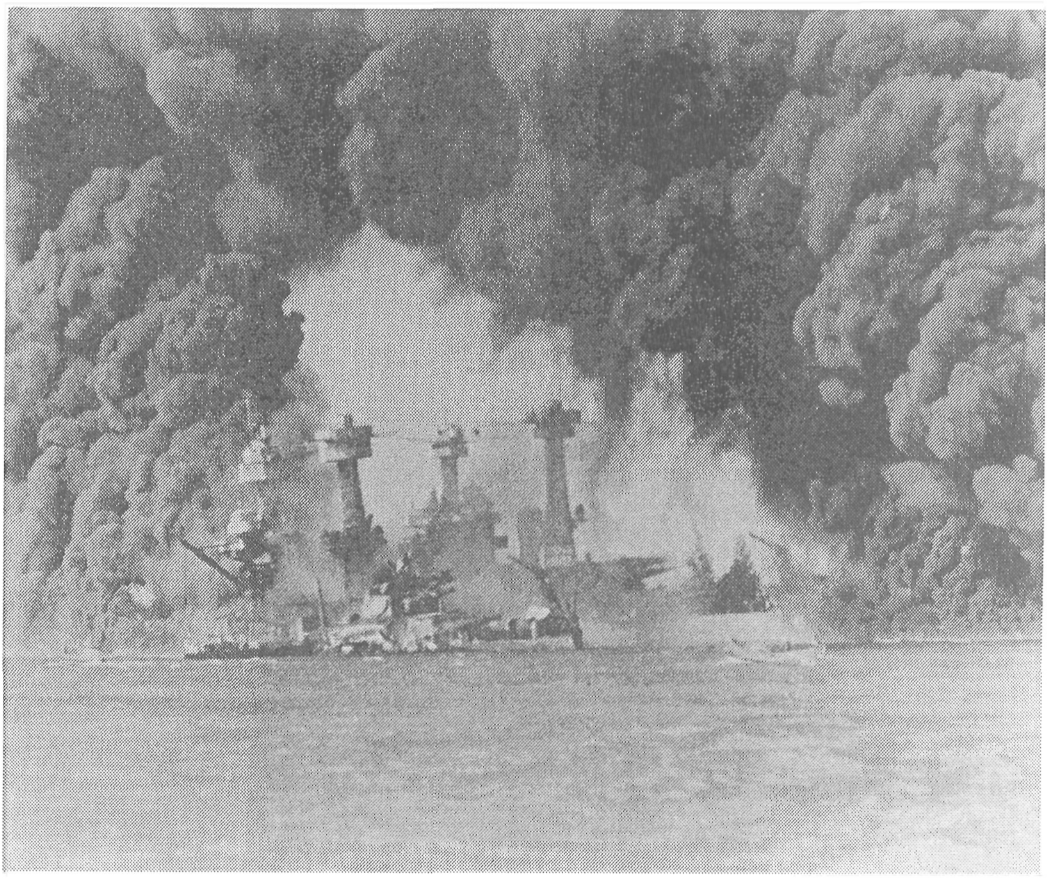

Figure 1.5: While topside on his way from *Pennsylvania's* main radio spaces to help set up the battle dressing station, McNally saw the harbor was a shambles of burning and exploding ships. The state of the battleships *West Virginia* and *Tennessee* can be seen in this photo. Note the CXAM radar antenna atop *West Virginia's* (closest ship to camera) foremast. *Official U.S. Navy photo.*

McNally heard all sorts of rumors about the attack. The men in Main Radio reported messages on the emergency broadcast frequency saying that Japanese landing parties were coming ashore, that the carrier *Lexington* had been sunk, and that the water supply had been poisoned. The firing died down and McNally went back to his room to see if anything was left. Nothing in his room was damaged, but his trunk full of blue uniforms was floating in the flooded passageway. He lifted the trunk and tied it to an overhead pipe to let it drain. For many years to come, the blue stain left in the trunk would remind him of that fateful day, and he would dwell on the question of why had he been spared? His life had literally been saved by following orders—when the young doctor had him go below to get the battle helmets [147].

Three hundred and fifty three Japanese carrier-based aircraft had been in the raid. Four U.S. battleships had been sunk, however two were later raised and repaired to return the favor to the Japanese. Three more battleships were severely damaged and one battleship, *Pennsylvania*, lightly damaged. Three light cruisers had been damaged, and one destroyer was damaged beyond repair, but most of its machinery was rebuilt into another destroyer given the same name. Two other destroyers were severely damaged but were repairable. One target ship was sunk and three auxiliary ships damaged [132, p.220]. To this point, the Japanese had proven that ships tied up in harbor were vulnerable to aerial bombs and torpedoes. Two days later they showed that capital ships proceeding in the open ocean were no safer. On 10 December Japanese land-based bombers and torpedo aircraft sank the British battleship *Prince of Wales* and the battlecruiser *Repulse* who were proceeding without fighter protection in the South China Sea near Singapore [46, pp.32–38].

Pennsylvania had to leave for the mainland as soon as she was fit for sea, and McNally needed new quarters; furthermore, the apartment in Honolulu was out of the question now because the Navy was shipping dependents home. Even though McNally was on CINCPAC staff as a radar officer, there were no quarters available, either in Navy housing or in the BOQ, but again he looked up a warrant officer friend, this time a marine warrant who got him a space and a folding canvas cot in the marine barracks bunkroom. The base marine warrant officers and noncommissioned officers shared this large bunkroom and ate in the same mess.

By the evening of 13 December, McNally had moved his belongings to the marine barracks and he was sitting down to a final meal with his shipmates on *Pennsylvania* when a messenger appeared and asked for him. The messenger said that McNally was to report to the aircraft carrier *Lexington* without delay, and that a CINCPAC boat was standing by to provide transportation. On 7 December *Lexington* had been at sea with Task Force 12 carrying a load of Marine Corps aircraft from Pearl Harbor to reinforce Midway Island, and had returned to Pearl Harbor on the 13th [147].

Aboard *Lexington*

Once aboard the CINCPAC boat, McNally learned that CDR Beard had directed that he report to *Lexington* as soon as possible and fix her CXAM-1 air search radar. It had been out of commission for several days and had resisted all attempts by *Lexington's* crew to make it work. McNally was quite familiar with the radar because he had studied its prototype, the XAF, at NRL, and he soon found the main problem was with the antenna. The CXAM-1 antenna was a large rectangular frame full of rigid dipoles and reflectors and was, for obvious reasons, dubbed a bedspring when it entered the fleet.

McNally ran some tests from the radar room and found that the bedspring would not rotate because of an inoperative training motor. The antenna was mounted on the leading edge of the smoke stack, so in blackout conditions McNally and two volunteer sailors ascended to the top of the stack and, in choking stack gas, unbolted the heavy train motor from its pedestal. Then they lowered it 100 feet to the flight deck. McNally found that the oil seal in the gear train had failed and had caused a short circuit in the motor which, in turn, had produced heavy armature current that had completely demagnetized the permanent magnet pole pieces.

When he took his direct current machinery course in college, McNally never expected he would ever put this course work to any practical use, but here was his chance. He wound a number of turns of magnet wire around the motor's pole pieces and then connected the magnet wire to the motor's power terminals. This turned the pole pieces into electromagnets. The electrical shop had a small hand compass that he used to determine correct magnetic polarities, and he used a bank of light bulbs, wired in parallel, to control the amount of current in the magnet wire. He reassembled the motor and connected it to the ship's DC mains. It ran, and he could control motor speed by adding or deleting light bulbs in his jury-rigged controller. Working through the night, by 0500 the next morning McNally and his volunteer assistants had the motor back in its pedestal on the stack.

Lexington had to get underway as soon as possible on the morning of the 14th to help relieve Japanese pressure on Wake Island. But there was still work to be done to get the CXAM-1 operable, and McNally was hard at work when *Lexington* steamed out of Pearl Harbor. The heavy train motor overload had also damaged circuitry in the amplidyne generator which controlled speed and direction of antenna rotation. McNally had to jury-rig this too. Using flashlight batteries and a potentiometer connected to the center tap of the amplidyne's differential control field, he made a manual servo that permitted smooth antenna direction and speed control.

McNally's next step was to try the CXAM-1's electronics. He lit the transmitter off and brought it up to full power with no problems, but the receiver drifted so badly it was impossible to keep it in tune. A new local oscillator 'acorn' tube, plus cleaning and tightening the tube mounting, cured the tuning drift.

Lexington's commanding officer, Captain Frederick C. Sherman, called McNally to the bridge for a status report on the radar, and McNally was able to give the CO good news. Captain Sherman told McNally that he had authorization to keep him on board as long as needed and that he had just one job—"to keep that radar running." McNally advised him he also had another job. "What would that be?" queried the CO. "That would be to teach your crew to do the same thing," replied McNally. The total secrecy surrounding radar up to that time had limited the number of persons who had radar training. In general, technical and operating knowledge as well as documentation of radar sets were sorely lacking.

By the evening of 14 December McNally had the radar back in full operating condition, but there he was, at sea with no written orders and nothing but the uniform he was wearing when he came on board. Captain Sherman directed that McNally be taken care of, and he was soon a member of the wardroom mess and assigned a comfortable room. Then McNally set up school and trained the two radio electricians and two chief petty officers until they were fully qualified to operate and maintain the CXAM-1.

Wake Island fell to the Japanese on 23 December and *Lexington* was recalled to Pearl Harbor, arriving back on 27 December. When McNally returned to his temporary quarters at the Marine Barracks he found a note to get in touch with his half brother Robert Sager, a crew member on the submarine *Grampus* which had just docked at the Pearl Harbor submarine base. They spent a pleasant evening recalling Minnesota boyhood memories, but it was the last time McNally would see his brother. *Grampus* was lost at sea in early 1943, and rests forever at the bottom of Blackett Strait in the Solomons [147].

Aboard the Flying Boats

McNally set out again to get the radar school project underway, but once more inoperable radars halted his plans. Commander Beard had new problems. The next day Beard drove McNally over to the Naval Air Station at Kaneohe where 12 Catalina patrol planes had just arrived from the mainland. They were equipped with British ASV airborne air search radar sets, and not a single one worked. Commander Beard helped McNally unload his personal gear from Beard's 'rickety old car' and helped move him into the Kaneohe BOQ. (McNally notes he never did manage to get into the Pearl Harbor BOQ.) Commander Beard's last words to McNally as he left for Pearl Harbor were, "Fix them Mac."

The patrol squadron gave McNally a spacious, well-equipped shop and he soon had a radar removed from one of the aircraft and set up on a workbench. There was not a scrap of technical documentation or descriptive material with the radar sets. "Apparently too secret," mused McNally. He set about tracing the circuits and preparing schematic diagrams. The unfamiliar British vacuum tubes (valves) and components threw him a little. But, electronics are electronics, and by the end of a long day he had the bench system operating. It was very gratifying to him to see the device come to life. To him it was like a musician mastering a very difficult, but beautiful, piece of music.

McNally's next problem was to determine why, even with the electronics operating in the aircraft, the systems were not generating target returns. He suspected a mismatch between the transmitter's frequency and the antennas installed on the airplanes. Could it be the radars had never been turned on and tested? He used an open wire transmission line (Lecher wires) and a neon bulb to measure the distance between standing waves along the line to find the transmitter's operating wavelength. He calculated the frequency to be 176 MHz, but his measurement of the Catalinas' Sterba curtain array antennas, which had been installed back at Norfolk, revealed they were designed to operate at 246 MHz—a definite mismatch.

McNally drew up a design for antennas that would operate at the transmitter frequency, and the Naval Air Station shops took care of fabricating and installing them. The next job was training each of the twelve air crews how to tune, adjust, operate, and troubleshoot the radars. To do this, McNally took a day-long patrol flight in each aircraft during which he gave the crew members hands-on training, and he accumulated 150 hours of payless flight time. The PBY radar rebuild and training took most of January and February 1942. Finally, the job done, Commander Beard came back in his vintage car and drove McNally back to Pearl Harbor so he could start again on his school for radar technicians [147]. We will return to McNally's story shortly.

The Fighter Director Officers

The principal job of the radar technicians was maintenance and repair of the radars as well as other types of electronic equipment. They sometimes operated the radars, but, in *Lexington* and most other carriers, the operating job usually fell to senior petty officers and assistant fighter director officers. At first, most fighter director officers were aviators, the rationale being they already knew the air end of the business, but senior officers, especially aviators, were divided in opinion whether aviators should be assigned to fighter direction. Some felt it too specialized and possibly harmful to the career of young aviators who should be getting cockpit time. Others maintained that only experienced aviators could do the job well. In the end, the logistics of the situation dictated the solution. Hundreds of new FDOs were needed which, along with other demands for aviators in nonflying jobs, drew too many trained aviators away from their primary job, with resulting fleet shortages. The solution lay in giving extensive fighter direction training to nonaviators.

In August 1941 the U.S. Navy sent its first class of future fighter direction specialists to the Royal Canadian Air Force Radio School for a five-week course in radar plotting and fighter direction. By September a similar U.S. Navy school was in operation at Naval Air Station, Norfolk, Virginia, and one month later the Pacific Fleet Fighter Direction School opened in San Diego [255, p.40].

On 1 October 1941 in an empty hangar at North Island Naval Air Station in San Diego, the first Pacific Fleet FDO School's class of 25 ensigns, including Ensign H. Stanwood Foote, assembled before the school's new commanding officer, Lieutenant Commander Jack Griffin. The student officers were all newly graduated from the U.S. Naval Reserve Midshipmen's School at Northwestern University, and LCDR Griffin had recently completed a tour as a U.S. Navy observer assigned to Royal Air Force and Royal Navy fighter squadrons. His mission was to teach what he had learned from the British about fighter direction. The new students found in a few minutes that the first step in learning to be an FDO at this school would be to help organize and equip the school, for the only physical asset the school had that morning was the hangar in which they were standing [101, p.1].

The students scoured Navy commands in the San Diego area to borrow copies of the many fleet tactical publications and manuals that would become their constant companions when they were fighter directors. Likewise they helped LCDR Griffin borrow, move, and install the basic equipment for the classrooms and for the air battle simulation setup in the hangar. They painted the hangar floor with a series of 10 concentric bullseye rings with bearing line spokes emanating from the bullseye's center—which was to represent task force center. To simulate airplanes, Griffin convinced the air station supply officer to order 12 of the largest available children's tricycles with chain driven rear wheels [101, p.5].

They made extensions for the seats and handlebars to allow a grown man to pedal the machines in relative comfort, and they made changes in the pedaling gear ratio to cause the trikes to move slower. The distance between each range ring was 10 feet, and that distance represented 10 nautical miles in most battle problems. A student piloting a tricycle representing an aircraft flying 300 miles per hour thus traversed the radial distance between two range rings in two minutes. This did not quite need vigorous pedaling. Precision timing in pedaling was much more important, and a table listing the number of pedal revolutions per minute needed to simulate various flight speeds was attached to each tricycle's handlebars in company with a magnetic compass and a clock with sweep second hand.

The students strung sound-powered phone lines from a catwalk high in the hangar down to each tricycle, and each tricycle pilot wore a telephone headset and a vision restricting hood. The hoods limited the distance at which the students could see other 'friendly' and 'enemy' tricycles to approximate the airborne view of a fighter pilot. Two students on the hangar catwalk, one with a bearing ring and one with a hand-held optical rangefinder, completed the simulation by phoning ranges and bearings of friendly and enemy tricycles to the classroom radar plot. Small radios were later substituted for the sound-powered phones and their dangling lines [101, p.6].

The trainees helped lay out a number of battle problems and then took turns riding the trikes, manning the 'radar station,' and working in the radar plotting room. In 'radar plot' they learned to chart the radar inputs with standard symbology and to work a maneuvering board to calculate the speed and heading commands they needed to transmit to their 'fighter trikes' to intercept the incoming enemy trikes. They learned correct fighter director radio telephone procedure and the lexicon to communicate with the fighters. From their own research they learned the characteristics of the radar models they would be using in the fleet. This included learning how to estimate target altitude from each radar type's fade zone chart. Then they helped write the radar characteristics textbooks for the classes that would follow them.

In the three-month FDO school, the candidates learned the basic doctrine, borrowed from the British, that every incoming raid should meet some opposition, even if it was just enough to disrupt enemy coordination. As opposed to British doctrine, which called for intercept about 30 miles from the ship formation, U.S. doctrine called for intercepts at the maximum range allowed by fighter endurance, by communications, and by accurate radar measurements. The future FDOs also learned that it was more important to have a reserve of fighters between the enemy and the formation to handle breakthroughs, than it was to initially hit the raiders with everything you had.

The FDOs learned four different intercept types. First they practiced them aboard their tricycles. Then they moved up to directing intercepts of light training aircraft, and finally graduated to directing first line fighters against high performance 'raiders.' They learned the head-on intercept which took few voice commands but was unforgiving in accuracy requirements. The orbit and wait intercept worked well in conditions of good visibility against small incoming raids, and the bracketing intercept, with defenders above, below, right, and left of the raid worked very well if you had enough fighters. Finally, they learned the controlled intercept which called for continuous vectoring information from the FDO to bring the fighter into firing position close behind his target in conditions of darkness or heavy weather [255, pp.42–43].

The curriculum also included enemy and Allied air tactics. This required the students to memorize the speed, turning, and climb capabilities; fuel capacities; fuel consumption at various speeds and climb rates; and weapons capabilities for each of the fighter types—Brewster 'Buffaloes,' Grumman F3F biplane fighters, and Grumman F4F 'Wildcats'—they would be controlling in combat [101, pp.5,7].

The content of the fighter direction school curriculum was not hard to define. What was more difficult was defining the set of innate personal abilities that would best support the fighter direction job [255, p.41]. The class members of LCDR Griffin's first San Diego FDO class had compared their backgrounds to try to find some common thread among them which might have brought them to the school. They found they were from diverse educational, skill, and interest backgrounds, and there was no common basis among them except for their graduation in the same class from the Naval Reserve Midshipmen's School [101, p.3].

Further Navy experience would show that the fighter director function had very little to do with flying skills, and it also did not demand scientists or engineers. What it did seem to demand was the ability to manage resources in a complex, fast moving situation. The FDO had to keep track of fighters in the air and also in reserve, plus those in a rearming and refueling status aboard ship. He had to know how to deploy each fighter type and its weapons to best advantage, and he had to be able to calculate when fighters should be relieved from station, when the carriers should be brought into the wind to receive aircraft, and how long it would take to rearm and refuel the fighters [255, p.41].

The fighter director also needed a good eye for relative motion in order to be able to vector his fighters at the right course and speed to intercept an incoming raid without coming in ahead of the raid or too far behind. He had to keep track of the sun's position with respect to his fighters and their intended targets, to keep his fighters 'up sun' of the enemy, and it was important to give your interceptors an altitude advantage over the enemy. If visibility was good, the pilots took charge of the attack as soon as they saw their targets, but in poor visibility it was sometimes necessary for the FDO to bring the interceptor into firing position very close to the target.

In essence, the job was a broad-based management function involving many details and a fast changing situation. What set of testable abilities and previous experience were good indicators that a candidate could handle such a job? The managers of the fighter direction officer training program eventually would find a high correlation between the candidates' previous civilian income and success as an FDO. One of their principal screening criteria would become a minimum total income of $30,000 over the preceding three years. They also wanted their candidates to be able to explain complex situations simply and succinctly, especially under stress. The program would take aboard many salesmen, lawyers, journalists, stockbrokers, and teachers. Teachers, however, would not have to meet the $30,000-in-three-years income criterion [255, p.41].

Twenty-two of the original 25 ensigns graduated in the first three-month Pacific Fleet FDO School class, and all were detailed to ships equipped with CXAM or SC radars. The highest scoring students, including Ensign H. S. Foote, went to aircraft carriers. In July 1942 LCDR Griffin would relocate the school to Camp Catlin Marine Corps Base in Hawaii in order to be nearer the Pacific scene of action [101, pp.4–5].

CXAM in Action

Lexington's CXAM-1 radar set was housed in a small compartment mounted on the front of the stack just below the bedspring antenna. The compartment was just big enough to accommodate the 6-foot-high by 5-foot-wide by 2-foot-deep CXAM-1 radar set and an operator's chair. A single telephone cord looped from the radar compartment down to the air plotting room at the rear of *Lexington's* bridge. Aside from four maintenance technicians, only six others in ship's company, including CAPT Sherman and his executive officer, knew what was in the little compartment and what the bedspring antenna was for. Fighter Director Officer LT Frank F. 'Red' Gill and his three ensign assistants were the rest of the six. The three assistant FDOs, including Ensign H. Stanwood Foote, took turns operating the radar set and plotting its targets on the dead reckoning tracer in Air Plot. The dead reckoning tracer was a glass-topped plotting table containing a mechanically driven 'bug' which projected the ships dead-reckoned position onto a sheet of tracing paper laid over the glass. The bug, in turn, was driven by an electromechanical dead reckoning analyzer that computed ship's position from speed log, gyro heading, current drift, and wind set inputs.

Air Plot in *Lexington* was a narrow compartment barely wide enough for the table-sized dead reckoning tracer, radio equipment, and a plotting team, who kept track of the carrier's airplanes, when airborne, by dead reckoning their flight paths and by pilot's position and sighting reports. After the CXAM radar was installed, the assistant fighter directors added the radar reports to the airplane position estimates already on the plot. Later, some carriers managed to work a small polar-gridded fighter director's plotting table into Air Plot to help manage individual air intercepts. It was a tight squeeze.

The fighter directors were forbidden to talk about the contents of the radar compartment or the purpose of the turning bedspring with anyone, so it can therefore be understood that their reports of air targets at ranges of over 100 miles were sometimes received with skepticism by bridge officers who had no idea of the set's workings or capabilities.

On 20 February 1942 McNally's investment in repairing *Lexington's* CXAM-1 radar and training her maintenance technicians paid off when the ship was enroute to launch an air strike against the Japanese base at Rabaul on the island of New Britain. At 1015 that morning as one of the assistant fighter directors was slowly training the bedspring antenna on the stack—with McNally's repaired train control—he saw a spike on his scope. He stopped the slow turn and cranked the antenna back to where the spike was a maximum. He glanced up and read target bearing from the antenna synchro receiver dial.

After reading the bearing dial, he read the range of the spike from a scale inked along the horizontal sweep. He pressed the button on his phone headset and called, "plot-radar." "Plot aye," came the response from Air Plot. "Air target bearing 351 degrees, range 52 miles." The men in Air Plot quickly verified that there were no known friendlies in that sector and classified the target as a probable 'bandit' (hostile aircraft). Then they relayed the probable enemy 'sighting' to the bridge [79].

Lexington launched Six Grumman F4F Wildcat fighters led by LCDR John S. Thatch who found a Japanese flying boat on the given bearing, and now 43 miles out from Task

Force 11. They shot it down, and a few minutes later LTJG O. B. Stanley, leading a flight of three aircraft, shot down a second flying boat to conclude the first radar directed air battle between aircraft of the Japanese and U.S. Navies. That afternoon the CXAM-1 operators spotted a number of attacking aircraft of the Japanese 25th Air Flotilla and helped coach *Lexington's* combat air patrol (CAP) fighters to intercept the two waves of nine each land-based bombers. The air battle took place in full view of *Lexington's* crew, and, between her fighters and her gunners, they knocked down 17 Japanese bombers. LT Edward (Butch) O'Hare, flying a Grumman Wildcat, alone brought down five [46, p.55].

The toll of Allied ships lost while proceeding without fighter air cover continued to mount. On 27 February 1942 nine twin-engined land-based Japanese bombers sank the American seaplane tender *Langley* at the mouth of Tjilatjap Harbor, Java, while *Langley* was attempting to ferry a load of 32 P-40 fighters to Tjilatjap, and on 5 April 1942 a force of 80 Japanese Navy dive bombers sank the British cruisers *Cornwall* and *Dorsetshire* outside Columbo, Ceylon. That same day the British aircraft carrier *Hermes*, having made an emergency deployment without her air group, was sunk by Japanese dive bombers in the bay of Bengal [46, pp.48–50].

Once again, in early March 1942, CDR Beard and McNally set out to get the radar school underway. By this time McNally's seniors on CINCPACFLT staff were trying to get him an officer's commission, but it had not yet come through, which was somewhat of a disadvantage. The Pearl Harbor Naval Base had assigned McNally's radar school project to the naval base public works office, but the brand new public works USNR ensign assigned to McNally's case had a difficult time understanding where a warrant officer fit into the scheme of things, and was less than cooperative.

McNally asked CDR Beard for help and got it in full measure. The radar school was high on Admiral Nimitz's priority list and LT Proctor Sugg, a former radio broadcast executive who had been aboard the stricken *California*, and LT William E. Kuntz appeared. They asked McNally to tell them exactly what he needed. LT Sugg, in particular, had the most amazing ability to beg, borrow, or steal anything McNally sought. Among other things, he soon had a jeep and a pickup truck for the school. The CINCPACFLT staff had the public works department removed from the project and arranged for a Navy Construction Battalion to take the job. The Sea Bees made rapid progress on the building, and on 1 May 1942 the school was ready for business [147].

Rest in Peace CXAM

On 20 February *Lexington's* fighters had fought the first radar-directed duel of World War II between U.S. Navy and Japanese aircraft. Later on 7 and 8 May 1942, *Lexington* took part in the first battle in history where aircraft carriers were pitted against each other—in the

Coral Sea. On 7 May *Lexington* and *Yorktown* launched 53 aircraft which sank the Japanese light aircraft carrier *Shoho* with numerous bomb hits and seven torpedo strikes. But on the following day aircraft from the carriers *Shokaku* and *Zuikaku* hit *Lexington* with bombs and five aerial torpedoes. Good fire fighting and damage control kept *Lexington* afloat, and while heading back to Pearl Harbor the crew began preparations to land her air group. But soon after the ship had set a course for Pearl Harbor, leaking aircraft fuel ignited in a major explosion that forced Captain Sherman to issue the abandon ship order [171, IV, p.105].

Assistant fighter direction officer Ensign Stan Foote heard the abandon ship order on the speaker in Air Plot, whereupon he unfastened his plotting sheet of the just completed air battle from the dead reckoning tracer, rolled it up and slipped it into a waxed cardboard tube. He sealed the tube and headed for his abandon ship station. Later, while Foote was in the water awaiting pickup by a friendly destroyer, the tube helped buoy him up. The destroyer and other ships rescued most of *Lexington's* crew, and then the destroyers sent *Lexington* to the bottom with five torpedoes. Rest in peace valiant ship and valiant men. Rest in peace CXAM.

After his pickup, ENS Foote was transferred from the rescuing destroyer to the cruiser *Astoria* where, from 8 to 12 May, he continued adding position data to his plotting sheet from *Astoria's* dead reckoning tracer. He then made a clean copy of the sheet which he sent to Captain Sherman who made it a part of *Lexington's* official Coral Sea action report [101, p.32][79]. Foote would then go on to increasingly responsible fighter direction duties aboard other aircraft carriers, and will later play a significant part in this story of how digital computers first went to sea.

The loss of *Lexington* to attacking airplanes generated concern among both *Lexington* and *Yorktown* officers that no matter how capable the fighter direction teams, the fighter direction facilities in both ships were totally inadequate. The lack of altitude measurement capability in their radars, the inability to electronically separate enemy from friendly aircraft, overcrowded fighter direction radio circuits, and general crowding and confusion in the small radar plotting room were attributed as direct reasons for *Lexington's* loss. In his Action Report for 8 May 1942, the Commanding Officer of *Yorktown*, *Lexington's* sister ship in the battle, had the following to say about his fighter direction facilities.

> The makeshift Radar Plot in this vessel, wherein all functions of Radar Plot are attempted to be accomplished in a corner of Air Plot, again showed itself, during the air attack on May 8, to be woefully inadequate to enable complete use to be made of all the information which the combined radars of own and other ships are capable of furnishing, or even to use with full effectiveness information which can be furnished by this vessel's one radar. In order that Radar Plot may properly perform its function it must:
>
> (a) Be, in itself, a complete unit.

(b) Have sufficient room to allow the Fighter Director and his plotting staff and communication assistants to perform their functions without mutual interference.

(c) Be so isolated as to be free from spectator interference and from noise interference from other activities. Both spectator and noise interference are unacceptably great with Radar Plot installed in a corner of Air Plot.

(d) Have its own radio communications, capable of transmitting or receiving on any aircraft circuit, and on a super frequency circuit with other search-radar equipped vessels and with other Fighter Directors.

(e) Be provided with interior communication channels connecting to signal bridge, lookouts, flag, and important ship and fire-control stations.

(f) Be contiguous to Air Plot and should have means for actual physical, conversational communications with Air Plot.

(g) Be provided with plotting facilities sufficient to allow two simultaneous radar plots to be run, one search plot, and a Fighter Director (tracking) plot.

(h) Have sufficient blackboard and extra chartboard space to allow a complete picture to be maintained of the situation of our own aircraft and of the general and immediate tactical situation. [28, pp.19–20]

The CO went on to note that *Yorktown's* radar had been inoperable during part of the action and recommended that all carriers should therefore have two long range radars equal in capability to the CXAM. He further recommended that, "... Distribution of aircraft radar recognition equipment should be continued with highest priority." Senior reviewing officers, aware of the expanded radar plotting rooms in new carriers such as *Hornet*, later commented on the *Yorktown* action report noting "this project is well in hand for new construction [28, pp.19–20]."

The CXAM Lives On

By early 1942 the CXAM radars on major fleet ships had proven indispensable, and afloat commanders were asking for sets with smaller antennas that could go on ships down to destroyer size. The experimental XAR radar which the Naval Research Laboratory had tested aboard the destroyer *Semmes* in July 1941 had 20 times more transmitter power (330 kW) than the CXAM and a much more sensitive receiver. These improvements, in turn, allowed smaller antennas. The XAR radar therefore became the prototype for a series of shipboard air search radars including Models SA, SC-1, and SK.

The best parts of the CXAM-1 and SC radars were then combined with the new plan position indicator (PPI) to become the SK radar, the U.S. Navy's best long-range air search radar from its introduction in 1943 until the end of the war. The Model SK with a large antenna was the first set able to detect medium size aircraft at 150 miles, prompting the Navy to contract with industry, under NRL guidance, to build hundreds of these models for all ship classes [91, p.183]. Then by 1943, in the quest for even more transmitter power, NRL developed the Model XBF shipboard search radar capable of 500 kilowatts at 200 MHz. The XBF served as the prototype for a series of radars designated Model SR, of which BUSHIPS had 300 built during 1944. The Fleet would depend heavily on the Model SR sets in the 1945 Pacific battles [91, p.186].

Turning Point for McNally

By June 1943 McNally's Pacific Fleet Radar Maintenance School had been in operation for a year, and an officer's commission at the rank of lieutenant junior grade had finally come through for him. Then, two weeks later, the CINCPACFLT staff arranged for McNally to be spot promoted to full lieutenant. By the end of the school's first year of operation, McNally had fully staffed the school with trained instructors, and they had prepared a curriculum emphasizing practical radar troubleshooting and repair, giving ship's radar officers and technicians intensive training on the specific models installed in their ships.

McNally was not content just to run the school. As ships returned to Pearl Harbor from combat deployments, he made a practice of visiting as many as he could as soon as they came in. He would check the condition of the radars, give advice and training and ask the crews what new features and capabilities they would like in their sets. He paid particular attention to the submarines and their new Model SJ surface search and targeting radar with which the submarine force was achieving deadly torpedo fire control success. The submariners were so appreciative of McNally's dockside visits, and for the support from his school, that Vice Admiral Lockwood, Commander of Pacific Fleet Submarines, invited McNally for a week of 'rest and rehabilitation' at the Royal Hawaiian Hotel which was reserved for returning submarine crews. Lockwood also visited McNally's school from time to time.

Submarines could make torpedo attacks in conditions of impossible optical visibility with the SJ radar, and the submariners loved the new radar. But it had one flaw in their way of thinking. It had a fairly visible rotating antenna atop the conning tower, and the submarines had to come close to the surface and raise the antenna to use the radar. The submarine officers asked, could they mount a workable antenna on the night periscope? McNally inspected a periscope and determined that there might be enough room to mount a very small radar antenna.

Figure 1.6: Lieutenant Junior Grade Irvin L. McNally on 1 May 1943 when he received his officer's commission at the Pearl Harbor radar school. McNally was spot promoted to Lieutenant on 15 May 1943 and then reported to BUSHIPS on 1 July 1943 where he was spot promoted to Lieutenant Commander. *Photo courtesy of Irvin L. McNally.*

He drew up a design for a small slotted waveguide antenna, built one, and tried it out temporarily strapped to a periscope. With his experimental periscope antenna, McNally found that the SJ radar could achieve detection ranges of 10 miles with 15 yard range accuracy. Because the antenna aperture was so small, the antenna had a 20 degree beam width, however they found by rocking the periscope back and forth they could determine the bearing of maximum signal return to within 1 degree.

In late June 1943 Vice Admiral Lockwood paid a visit to the Radar School, during the course of which he asked McNally about the possibility of putting a radar antenna on an optical periscope. McNally's response, "I think we have the answer Admiral," changed the course of McNally's life. McNally showed him the small antenna with which he and the submariners were experimenting. The Admiral made a quick phone call, and the next day Lieutenant McNally was on the Pan American Clipper to San Francisco, and thence to Washington, D.C., to join the Radar Design Branch in the Bureau of Ships. His first assignment was to complete design details of his periscope antenna and get it into production. McNally would spend the next seven years in BUSHIPS, and we have not heard the last of him [148].

Evolution of the Combat Information Center

In response to recommendations from the fleet, BUSHIPS and NRL added improvements to each new radar model as it came out. In early 1942 the first plan position indicator (PPI) displays had begun appearing in the fleet to supplement the A scope displays, and they soon became standard in conjunction with the A scope. BUSHIPS also improved the PPIs with ships heading indicators, and with electromechanical cursors for faster and more accurate range and bearing readout. The designers incorporated height finding features into some radar models, and identification-friend-or-foe became a standard feature of nearly every air search model.

As with the A scopes, the radar designers built the first PPIs directly into the radar set control units. But the radar sets had to be located relatively close to their radar antennas to keep the transmission line from set to antenna as short as possible, whereas the radar plotting rooms had to be located in other parts of the ship near the consumers of the radar information. This meant, even though the radar operators had an easier-to-comprehend display and they no longer had to stop the antenna on a target, they still had to send target data by voice or messenger to Radar Plot.

In one attempt at speeding up target data transfer, the sailors used circular sheets of translucent paper laid over the PPI display. The operator quickly traced the locations of the blips during one rotation of the sweep, and then annotated a bearing marker and the range scale. A messenger ran the sheets to Radar Plot. Sailors have a name for everything, and these circular sheets were no exception. They were 'cookies' [147]. But cookies were not the ultimate solution. It was better to bring live PPI displays to the many users.

By the end of 1941 there was also a movement to install more than one radar in new construction ships. Some large combatants got two identical long-range air search radars to handle increased tracking loads and to back each other up in case of casualty. For example, new aircraft carriers generally got two SK air search radars and a backup SC-2 radar which was similar to the SK but had a smaller antenna. Existing large combatants were also slated to get more radars during their shipyard overhaul periods, and the radar designs were becoming more specialized, branching into air search and surface search—such as the magnetron-based SG surface search radar—not to mention gunfire control and height finding applications [255, p.43].

In early 1942 as multiple search radars were being installed in the larger ships, there was a tendency in ship layout to try to group all of the radar sets and many of the consumers of radar information, such as Air Plot, Submarine Plot, and Gunnery Plot into one shipboard location. There was considerable operational value in placing the people who were responsible for managing anti–air, anti–submarine, and anti–surface warfare into a common room to share information and compare notes with each other. But the result was a hot (because of all the vacuum tubes in the electronics), crowded, noisy space.

It was soon obvious that, other than the value of having the radar plan position indicators in the new combined plots, there was no compelling need to have the heat producing radar transmitter/receiver sets in the same room with the radar plotting teams. The best solution was to separate the PPI scopes from the radar set controls and locate only the PPI displays with the users. Remote PPI displays called 'repeaters' were the solution.

The idea of a remote PPI repeater had been in the works since 1939 when Naval Research Laboratory engineers testing the experimental XAF radar aboard USS *New York* saw that radar could be much more useful if its displays were located at the users' stations such as the air and gunnery plotting rooms. To that end, they planned to begin work on a PPI repeater with a priority immediately following development of the basic plan position indicator. In their concept, one radar could drive many PPI repeaters.

By mid 1942 NRL had completed a general-purpose remote PPI repeater, designated Model VD, the 'V' standing for video display and the 'D' representing the fourth model in a series of PPI display models. The VD, with its four fixed range scales, was considered the fleet's first satisfactory radar repeater [91, p.194]. The PPI repeater allowed the layout designers to leave the radar transmitter/receiver rooms in locations where they could have short waveguide runs to their antennas, and to concentrate only the repeaters from the various radars in one area.

The fighter directors found by grease penciling successive sweeps of a radar target on the face of their PPI repeaters they could develop a plot of target movement and could estimate its speed and heading directly from the scope. The PPI repeater plot also had the great advantage of being no older than the 15-to-30-second radar sweep period whereas the plotting table tracks were usually two to four minutes old, which contributed to errors in fighter direction. The FDOs now had the options of using their plotting tables or of controlling intercepts directly from their PPI repeaters [28, p.11].

In November 1942 Commander-in-Chief, Pacific Fleet gave the consolidated shipboard radar plotting rooms a new name: the combat operations center (COC), and he proposed establishing a COC in every combatant ship. In his concept, the COC would augment the grouped PPI displays with status boards and large edge-lighted plexiglass vertical summary plotting boards which could be seen throughout the COC. The space would also have numerous radio channels and interior communications circuits to facilitate fighter direction, task force communications, and information transfer with own-ship control centers such as the bridge, sonar room, gunfire computer rooms, radar rooms, main engine control, damage control central, and lookouts.

The combat operations center was also to have facilities to keep it current with ship's navigation data, weather, and changes in the strategic and tactical situation. It was to have primary control of all own-ship's radars, subject to overriding orders of the group or force Officer in Tactical Command. When the ship was designated a fighter director ship or a radar guard ship, the COC was to broadcast information on all assigned air targets [28, p.30]. In 1943 BUSHIPS augmented the COCs with the Model SM and SP radars, the first fighter direction radars with height finding capability [91, pp.189,194]. The air intercept plotting tables, as well as the dead reckoning analyzer and the dead reckoning tracer, were also moved into the new COC. Further, synchro target designation transmitters appeared next to the gunnery coordinators' PPI scopes to allow gunnery officers to send surface and air target positions to the gun directors.

Some senior officers bridled at the phrase 'combat operations center' as taking precedence over the bridge as the place where combat operations were traditionally directed. Their sentiments prevailed and in a few months the combat operations center became the 'combat information center' (CIC) [28, p.30].

Even with removal of the radar sets, there were still many heat-producing electronic units in the CIC spaces. This caused the CICs to become one of the few locations in a ship to be air conditioned. Also, handling fast changing combat information meant considerable talking, so the spaces were heavily sound proofed. In order to have good visibility of the target blips on the radar repeater faces as well as the glowing grease pencil marks on the edge-lighted summary plots and status boards, the CIC was kept in a darkened condition. The main lighting came from the glow of the radar repeaters, the backlit plotting tables, and an occasional small shaded reading lamp turned on only long enough to read a message, a paragraph in a signal book, or an operations manual.

In battle, a large volume of information came into the CIC fast, many decisions had to be made in a hurry, and much information went out. Early CIC practitioners said the real meaning of the acronym 'CIC' was 'Christ I'm Confused.' But they knew they would have been much worse off without the combat information center.

In 1942 night surface actions off Guadalcanal, American surface forces barely held their own in encounters with Japanese surface forces. American cruisers especially were victims in disproportionate numbers to torpedoes in the nighttime battles. One of the problems was the amazing range and effectiveness of the Japanese Type 93 'Long Lance' torpedoes, and another was the well-rehearsed, well-coordinated Japanese tactics for using the torpedoes. The Americans did have the advantage of their air search radars that were somewhat effective in finding surface targets in the darkness. But the air search radars were not particularly designed to detect surface targets.

The night surface action at Kula Gulf, Solomon Islands, on 6 July 1943 marked a turning point in the problem. By this time every U.S. combatant ship from destroyer up was equipped with the new SG surface search radar, and more importantly, all were outfitted with combat information centers. The initial Kula Gulf battle assessment was six Japanese ships sunk to the loss of the U.S. Light Cruiser *Helena.* The official score was later changed to two Japanese destroyers confirmed sunk, because of the difficulty of proving enemy losses from radar data or from the flames of burning ships that left little evidence in the morning.

By 25 November 1943 at the Battle of Cape St. George near the island of New Britain, the results were much clearer in an even-odds night engagement of five U.S. destroyers against five Japanese destroyers. Three Japanese destroyers went down with no American ship losses. The contribution of the combat information centers in organizing, assessing, and sharing radar information among ships, and in coordinating ships' tactics, was credited as a major factor in improving the score in night surface actions [105, pp.114–115][191, p.104].

Even though the fighter direction officers, the principal users of the large CIC facilities installed in aircraft carriers, carried unusually heavy responsibilities, most were less than 30 years old and were relatively junior in rank. In the fleet organization there was formed a hierarchy of fighter direction officers ranging from a small FDO organization on a destroyer, to task group and task force fighter direction officers. The task group or task force FDOs managed air defense of the entire formation, including handing out fighter direction assignments to other ships. In this business, ability and demonstrated results were more important than rank or age and, as the Pacific war moved on, it would not be unusual to see a lieutenant or even a lieutenant, junior grade, handling the awesome responsibility of directing task force air defense. LTJG John B. Connally, Task Group 38.3 FDO during the Battle of Leyte Gulf, LT H. S. Foote, by April 1945 Task Force 58 Combat Information Center Officer (CICO) during the Kamikaze-plagued Okinawa invasion, and LT John McGinnis,

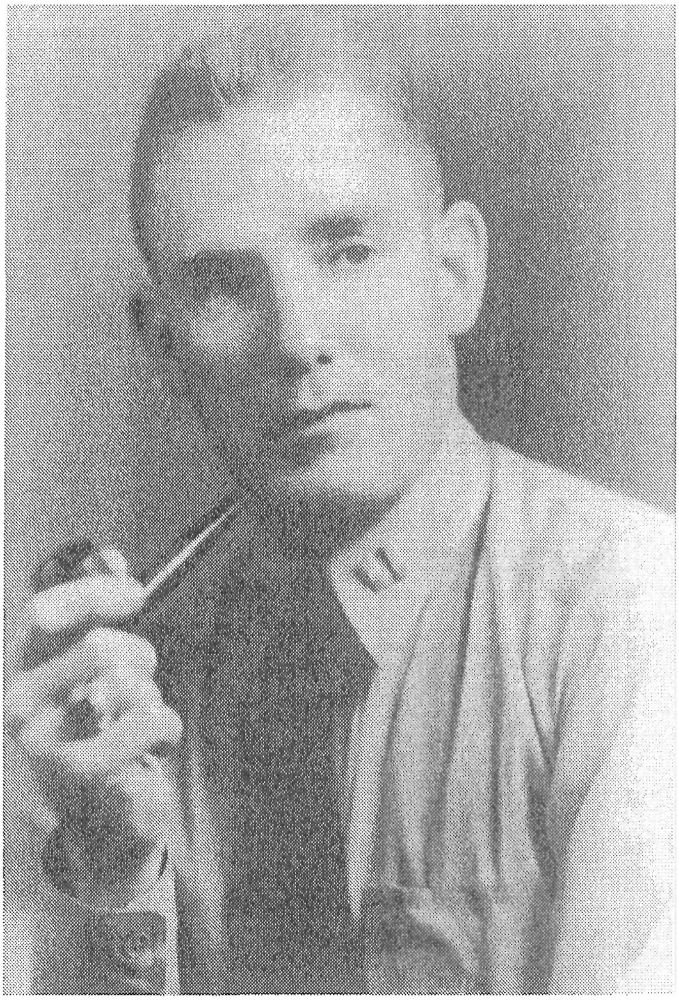

Figure 1.7: Task Force 58 Fighter Direction Officer Lieutenant H. Stanwood Foote, September 1943. *Photo courtesy of CAPT H. Stanwood Foote.*

Admiral Halsey's TF 38 CICO during the same operation, are other examples; as well as Task Force CICOs LT Charles Ridgway and LT Nicolas J. Hammond [255, p.41][81].

The Kamikazes

Divine Wind

On 19 October 1944 when Vice Admiral Takajiro Ohnishi proposed the idea of a suicide attack squadron to the pilots of the 201st Air Group Fighter Squadron based at Mabalacat in the Philippines, all 23 of the petty officer pilots stepped forward. The next day Ohnishi formed the Shimpu Attack Unit around the 23 young volunteers and their 26 Mitsubishi Zero 32 fighters, which were modified to carry a 550-pound bomb. This was the start of the Navy Special Attack Corps which they named 'Kamikaze,' meaning Divine Wind, after the Japanese wind god who is credited with saving Japan by sinking the Mongol invader Kublai Khan's supply ships with a typhoon in the year 1281. The practice would grow to the extent that, by the end of hostilities in 1945, approximately half of the ten thousand remaining Japanese Army and Navy aircraft were marked for suicide squadrons, and five thousand suicide pilots were in training [27, pp.18,37,78].

The intent of the Japanese Army fighter bomber pilot who, on 21 October 1944, flew into the bridge of the heavy cruiser HMAS *Australia* in Leyte Gulf will never be known. But in the resultant death of *Australia's* commanding officer and 21 other men, he effectively carried out the first suicide attack of the campaign [27, p.19]. Then on 25 October, five Special Attack Corps volunteers took off from Mabalacat in their modified Zero fighters with 550-pound bombs. Their mission was to hit American aircraft carriers that had just launched an attack against Japanese carriers off the Philippines. In the general melee of other conventional aircraft attacks, the new Kamikazes were perceived by the defenders as no different than any other attacker, until one dove into the escort carrier *Santee*, setting it afire. Another made a direct crash into the escort carrier *Suwannee*, but the carrier was able to recover aircraft and continue operations. One Special Attack Zero also managed to penetrate the escort carrier *St. Lo's* flight deck and explode the ship's ammunition stores. *St. Lo* blew up and sank, to become the first warship sunk by airborne suicide attack [46, p.123].

In the past, Japanese pilots had sometimes accidentally and sometimes deliberately flown damaged aircraft into Allied ships, but by the end of October the number of undamaged aircraft deliberately crashing into ships made it clear that the Allies were facing a new mode of warfare. The Allied reaction was increased lookouts and more intensified radar vigilance accompanied by increased combat air patrols, with special emphasis on low altitude-patrols. The suicide attackers had shown a pattern of approaching the ship formation at low altitude until a few minutes from their target when they would zoom up to about 5,000 feet for their final dive [27, p.24].

To help overcome the Japanese Zero fighter's speed and maneuverability advantage over the U.S. Navy's F4F Wildcat fighter, Lieutenant Commander J. S. 'Jimmy' Thatch had devised the 'Thatch weave' in 1942. In this maneuver a Wildcat, with a Zero on his tail, led the trailing Zero into his wingman's gun sights. The tactic was so effective that it was adopted by the U.S. Army Air Corps, the RAF, and even by the Japanese. Later, in 1944, while serving as operations officer for Task Force 58, Thatch was called upon to help devise new tactics to counter the Kamikazes [210, pp.65,157]. By December 1944 Thatch had worked out and tested a new system of fleet defense in depth which was to be combined with new offensive tactics [27, p.34].

For improved defense in depth, Thatch called for stationing early warning radar picket destroyers fitted with special height finding radar, as well as long range air search radar, 50 to 60 miles outside the main body of the task force in the expected direction of the threat. Each picket had assigned fighter patrols orbiting overhead 24 hours a day. The fighters had the dual purpose of protecting the pickets, and also, under the coaching of fighter directors aboard the picket destroyers, they were to intercept any unidentified inbound track.

Closer to the task force, Thatch strengthened the continuous fighter patrols and split them from their normal 20,000-foot patrol altitude into a 'HiCap' above 25,000 feet and 40 miles out, and a 'MedCap' at 10,000 feet and 20 miles out. Then, just outside the destroyer gun screen, 'JackCap' fighters patrolled below 3,000 feet to catch Kamikazes who might get through the two outer fighter screens. The task force commanders also moved the task groups closer together to fill in radar coverage gaps caused by fade zones, and to allow more responsive mutual protection by making it easier to loan CAP aircraft to a neighbor under attack [27, p.34].

The new tactics reduced the Kamikaze threat but did not eliminate it. On 21 February 1945 a Japanese suicide aircraft operating from the Japanese home island of Kyushu hit and sank the escort carrier *Bismarck Sea*, and five Kamikaze Zeros piled into USS *Saratoga* in three minutes. *Saratoga* survived but spent the rest of the war under repair. On 19 March the carrier *Wasp*, operating off Kyushu, suffered a bomb hit causing heavy casualties, and the same day the carrier *Franklin*, also operating off Kyushu, was hit by a single aircraft that slipped through the aerial screens. Then on 20 March a Kamikaze severely damaged the destroyer *Halsey Powell* [46, pp.140,145].

By September 1944, the Yokosuka Naval Air Arsenal was building a manned, rocket-boosted flying bomb called the Cherry Blossom (Ohka) for use against ships. The Ohka's builders considered dispensable human guidance an acceptable solution [27, pp.14–18]. The first squadron of Ohkas went operational under Vice Admiral Matome Ugaki on 10 February 1945, but he did not immediately employ them. He saved them for a suitable high-value target, and on 21 March his scouting aircraft found the 'suitable' target—Allied Task Force 58 operating off Kyushu, and apparently without fighter protection. Ugaki launched a flight of 30 protective fighters and 18 Mitsubishi G4M 'Betty' bombers, each carrying one Ohka manned bomb.

When the attackers came within 100 miles of the task force, they lit up the task force radars. Given the advance warning, Task Force 58 put 150 Corsair and Hellcat fighters in the air to meet the attackers. The fighter directors assigned the Corsairs to the protecting Zeros, and 20 Zeros fell victim to the new inverted gull wing fighters, while the Hellcats worked over the mother airplanes. None of the mother aircraft reached their 'standoff' launching range before the Hellcats shot down all 18. The Cherry Blossom did not score this time, but there would be other opportunities [27, p.59].

Floating Chrysanthemum

The Ohka attack on TF 58 might have been much more effective had the Japanese coordinated it with other suicide and conventional attacks coming from other directions. As it was, TF 58 had the luxury of concentrating fighters from four task groups to oppose the single raid. In April 1945, under the pressure of an Allied invasion fleet landing troops on Okinawa, the Japanese got their aerial tactics together. On 6 April 1945 they started a new form of massed Kamikaze and conventional attack called Kikisui or 'Floating Chrysanthemum' wherein 900 Japanese aircraft, approximately one third of which were Kamikazes, attacked the Okinawa invasion fleet [27, p.59]. They sank three U.S. destroyers, two ammunition ships, and one tank landing ship. Task Force 58 pilots claimed 249 Japanese aircraft downed. The next day, continuing the same saturation tactics, a Kikisui attack damaged the battleship *Maryland*, two destroyers, and the carrier *Hancock* [46, pp.147,150].

On 11 and 12 April the Japanese launched a second massed attack on the Allied invasion fleet, this time with 185 Kamikazes, 150 fighters, and 45 torpedo bombers. On the second day of the attack, a piloted Ohka bomb claimed its first victim, the destroyer *Mannert L. Abele*, hit and sunk by a single Ohka. Task Force 58 gunners and fighters shot down 298 Japanese aircraft in this attack, but the massed air attackers also damaged an Allied battleship and two carriers [46, p.150].

One hundred and sixty Japanese aircraft formed the third Kikisui attack on 16 April. This time they sank ammunition ships and minesweepers. The fourth Kikisui attack came on 28 and 29 April, targeting the outer radar picket ships and escorts, but none were hit. Thatch's defensive tactics were working [46, p.151]. The next massed Kikisui attack on the Okinawa invasion force on 3 and 4 May again concentrated on picket ships and auxiliaries on the force perimeter. The raiders sank three picket destroyers and three landing ships, causing picket station duty to cost 370 U.S. sailor's lives on 4 May alone.

In the sixth Kikisui attack, staged during the period 11 through 13 May, 250 Japanese attackers severely damaged two destroyers, and a Kamikaze hit Admiral Mitscher's flagship, *Bunker Hill*, killing eleven of the Admiral's staff. Mitscher was forced to transfer his flag to USS *Enterprise* which took a Kamikaze hit on 14 May. One allied destroyer was sunk during the seventh Kikisui attack from 23 to 25 May, and the last Kikisui on 27–29 May netted one U.S. destroyer. There were no more massed suicide attacks. The Japanese high command realized they were running out of pilots, and that they must conserve the remainder for homeland defense [46, p.152].